I. Natural Hazards
D. Geological Hazards

The following outline summarizes the significant geological hazards covered in this section:

1. Ground Movement
    a. Earthquakes
    b. Subsidence
2. Celestial Impacts

Although some states recognize "landslides" as an additional hazard, Michigan's geology and history tends to make it more prone to land subsidence instead. Michigan's two main vulnerabilities to ground movement are therefore identified in the sections on earthquakes and subsidence hazards. Erosion is not in itself typically considered an emergency event, except in cases involving encroachment into shoreline developments near a river or lake, and these have been dealt with in the Hydrological Hazards section of this plan. A new section of this plan, celestial impacts, deals not only with the impact of physical objects on property, but also with the effects of solar storms on our modern infrastructure. It will be seen that the systemic technological impacts of this hazard involve greater expected risks than the more well-known impacts of a meteoritic type. Although meteorite impacts are quite easy to understand and visualize, and do have a small potential to be catastrophic, it is the seemingly abstract and mostly invisible effect of "space weather" that has the greatest probability of causing widespread disruption and harm in the near future.

Overlap Between Geological Hazards and Other Sections of the Hazard Analysis

The most serious Michigan earthquakes would be expected to damage some of the utilities infrastructure in the southern part of the state, and could contribute to the occurrence of an energy emergency. Some flooding could result from broken water mains. There may be some potential for oil and gas pipeline operations to be disrupted, as well. A serious subsidence event may cause a key roadway to collapse and become unusable, and may also cause certain other types of infrastructure to become exposed and vulnerable. Transportation accidents that may result from these hazards could cause the release of dangerous hazardous materials. The real potential for a catastrophic incident exists in the event of a major seismic event involving the New Madrid fault line.

Celestial impacts involving solar flares can cause infrastructure failures and have the potential to cause major transportation accidents involving airplanes and/or seagoing vessels. Other types of celestial impacts, involving the impact of physical bodies upon the Earth and its atmosphere, are usually minor but rarely will have the potential to be catastrophic, capable of causing damage equivalent to a nuclear attack and the associated casualties, mass fires (including wildfires), infrastructure failure, severe winds, and physical damages associated with the nuclear attack hazard (but without as intense of radiological effects).

Earthquakes

A shaking or trembling of the crust of the earth caused by the breaking and shifting of rock beneath the surface.

Hazard Description

Earthquakes range in intensity from slight tremors to great shocks. They may last from a few seconds to several minutes, or come as a series of tremors over a period of several days. The energy of an earthquake is released in seismic waves. Earthquakes usually occur without warning. In some instances, advance warnings of unusual geophysical events may be issued. However, scientists cannot yet predict exactly when or where an earthquake will occur. Earthquakes tend to strike repeatedly along faults, which are formed where tectonic forces in the earth's crust cause the movement of rock bodies against each other. Risk maps have been produced which show areas where an earthquake is more likely to occur. Earthquake monitoring is conducted by the U.S. Geological Survey, the National Oceanic and Atmospheric Administration, and universities throughout the country.

The actual movement of the ground in an earthquake is seldom the direct cause of injury or death. Most casualties result from falling objects and debris. Disruption of communications systems, electric power lines, and gas, sewer and water mains can be expected. Water supplies can become contaminated by seepage around water mains. Damage to roadways and other transportation systems may create food and other resource shortages if transportation is interrupted. In addition, earthquakes may trigger other emergency situations such as fires and hazardous material spills, thereby compounding the difficulties of the situation.

A fault line is where a fault meets the ground's surface, but many faults dip at an angle away from their surface location, and therefore earthquakes that occur at some depth will often not line up with the fault at the surface. Faults do not only occur at the boundaries of large geological plates. There are many small plates that exist, as well as faults that are internal to or perpendicular to plate boundaries.

Hazard Analysis

No severely destructive earthquake has ever been documented in Michigan. However, several mildly damaging earthquakes have been felt since the late 1700s. The exact number is difficult to determine, as scientific opinion on the matter varies. With most of these earthquakes, damage (if any) was limited to cracked plaster, broken dishes, damaged chimneys, and broken windows.

In recent years, attention has been focused on the New Madrid Seismic Zone. This zone extends from approximately Cairo, Illinois through New Madrid, Missouri to Marked Tree, Arkansas. During the winter of 1811-1812, a series of earthquakes shook the area. The three worst earthquakes destroyed the town of New Madrid, created a 17,000 acre lake in Northwestern Tennessee, and caused ocean-like swells on the Mississippi River. Richter Scale estimates ranged around 8.0. The 1811-1812 earthquakes also included hundreds of aftershocks, some with magnitudes estimated to be between 6.5 and 7.6 on the Richter Scale.

The New Madrid Seismic Zone is significant because scientists predict that a catastrophic earthquake (between 6.0 and 7.6 on the Richter Scale) will occur within the zone sometime during the next few decades. Michigan may be somewhat affected by such an earthquake. A repeat of the 1811-1812 earthquakes is unlikely in the near future. However, should it occur, it could result in damage, disruptions, casualties, and injuries on a scale never experienced from an earthquake in the history of the U.S. The immediate and long-term relief and recovery efforts could place a significant, prolonged burden on the regional and national economies.

Fortunately, Michigan is not located in an area subject to major earthquake activity. Although there are faults in the bedrock of Michigan, they are now considered relatively stable. However, these faults are poorly mapped. According to the U.S. Geological Survey, although Michigan is in an area in which there is a low probability of earthquake occurrences, the area may be affected by distant earthquakes that occur in the New Madrid Seismic Zone and upstate New York. The New Madrid Seismic Zone poses the most significant threat. Based on recent scientific studies, portions of southern Michigan could be expected to receive minor damage were such an earthquake to occur (see the map at the end of this section).

The greatest impact on the state would probably come from damage to natural gas and petroleum pipelines. If the earthquake occurs in the winter, many areas of the state could be severely impacted by fuel shortages. Damage would probably be negligible in well-designed and constructed buildings. However, poorly designed and constructed buildings could suffer considerable damage under the right circumstances.

The following table has a list of earthquakes that have been felt in Michigan. The most severe event centered in Michigan was the 4.7 magnitude event of 1947, which caused some damage to (mainly residential) structures in the southwest region of the Lower Peninsula.

Tectonic Earthquakes Felt or Occurring in Michigan

Date	Origin	Magnitude
4-20-1793*	Porcupine Mt, MI	N/A
12-16-1811 (3 events)	New Madrid, MO	7.9, N/A., N/A
1-22-1812	New Madrid, MO	N/A
1-23-1812	New Madrid, MO	N/A
1-25-1812	New Madrid, MO	7.0
2-3-1812	New Madrid, MO	N/A
2-7-1812	New Madrid, MO	7.5
2-8-1812 (4 events)	New Madrid, MO	N/A
10-20-1870	La Malbaie, QUE	N/A
8-17-1877*	Greenfield, MI	3.2
9-19-1884	Lima, OH	4.8
9-1-1886	Charleston, SC	7.7
10-31-1895	Charleston, MO	6.7
5-26-1909	Aurora, IL	5.1
3-1-1925	La Malbaie, QUE	7.0
8-12-1929	Attica, NY	5.2
11-1-1935	Timiskaming, QUE	6.2
3-2-1937	Anna, OH	5.0
3-9-1937	Anna, OH	5.4
2-12-1938*	Porter, IN	4.0
3-13-1938*	Gibraltar, MI	3.8
3-14-1938*	Gibraltar, MI	N/A
3-9-1943	Lake Erie, OH	4.5
9-5-1944	Massena, NY	5.8
8-10-1947	Coldwater, MI	4.7
11-9-1968	El Dorado, IL	5.5
9-15-1972	Rock Falls, IL	4.5
4-3-1974	Lancaster, IL	4.7
2-2-1976	Pt. Pelee, ON	3.4
7-27-1980	Sharpsburg, KY	5.1
8-20-1980	Harrow, ON	3.2
11-29-1982	Scotts, MI	2.5
10-7-1983	Blue Mtn. Lake, NY	5.1
1-31-1986	Perry, OH	5.0
7-12-1986	St. Mary's, OH	4.6
6-10-1987	Lawrenceville, IL	5.2
11-25-1988	Saguenay, QUE	5.9
9-2-1994	Central Michigan	3.4
9-25-1998	Sharon, PA	5.2
10-23-2001*	Prairie Lake, MI	2.9
4-18-2008 (2 events)	West Salem, IL	5.4, 4.8
2-10-2010	Elgin, IL	3.8
6-23-2010	Val-Des-Bois, QUE	5.0

N/A means that the magnitude information was not available.
* May not have been a natural earthquake. Explosive blasting, mine collapse or other subsidence, and large meteorite impacts can all cause tremors to be felt that may give persons the impression that an earthquake has occurred.
Source: Michigan State University Earthquake Information Center / East Lansing Seismic Station

NOTE: This list has been adapted from the "Earthquakes in Michigan" source list found at https://www.msu.edu/~fujita/earthquake/eqinfo.html. Earthquakes that may not have actually been felt in Michigan were not included in the list.

Historical earthquake occurrences appeared to have an element of a cyclical nature about them, with some decades containing numerous events, surrounded by decades with only a few events, and followed by periods with nearly no occurrences at all. Over time it may be that (probably due to increases in population and development) the number of occurrences gradually increases within this cycle, although this is uncertain. (The pattern is not extremely clear and long, and may just happen to be a statistical artifact.) The potential pattern is illustrated through the listing of natural tectonic earthquake events by decade, with arrows pointing to small peaks of earthquake activity approximately every 50 years. (This is shown on the next page.)

The hypothesis that there may be a kind of cyclic trend is based purely upon the historical data. A recent text, Michigan Geography and Geology (editor in chief, Randall Schaetzl), includes a chapter on earthquakes and states that "about once every 50 years, a magnitude 3-4 event occurs within the state, south of a line between Grand Rapids and Pontiac." Although the event information (listed above) had fit pretty well into this pattern, the most recently updated information from the same source has not quite fit perfectly into the proposed pattern, for instead of the earthquake activity dropping to zero after a clear peak during the 1980s, it has instead fallen into a pattern of about two events per decade, and one of those decades (the 2010s) has only just begun! Thus, there seem to be more earthquakes being felt recently than might have been expected, according to the previous pattern. It is possible that this level of disturbance might be comparable to the periods that would have been marked with zeroes in the past, and that the next occurrence of a peak (in the 2030s?) may therefore involve a record number of events, if there is indeed a gradual trend toward an increased number of disturbances.

1790s:	0	
1800s:	0	
1810s:	12	←These were all New Madrid events and aftershocks, and may not fit into a cyclic trend for Michigan
1820s:	0	
1830s:	0	
1840s:	0	
1850s:	0	
1860s:	0	
1870s:	1	
1880s:	2	←Possible peak in a cyclic trend
1890s:	1	
1900s:	1	
1910s:	0	
1920s:	2	
1930s:	3	←Possible peak in a cyclic trend
1940s:	3	
1950s:	0	
1960s:	1	
1970s:	3	
1980s:	8	←Possible peak in a cyclic trend
1990s:	2	
2000s:	2	
2010s:	2	←Recent trend might not quite match the proposed 50-year cycle

Earthquake Risk Calculation

Although earthquakes are generally not considered a major hazard in Michigan, other states have had so many problems with this hazard that very detailed techniques have been developed to estimate earthquake risks. Each area of the country has been assessed by geologists (according to types of bedrock, fault line proximity, and other factors) and sorted into general zones of earthquake risk. (For a national map showing this, see the web site at http://earthquake.usgs.gov/research/hazmaps/.) These zones are expressed in terms of a probability that significant ground movements will be felt. For example, there may be a 10% chance of an area experiencing significant ground movement within a 50 year period, (which is similar to the "500-year" floodplain, since the annual probability of such an event calculates as roughly .0021). Another component of risk calculation would be to estimate the amount of damage that is likely when such an event occurs. Official measures use the concept of Peak Ground Acceleration (PGA, which is also abbreviated as %g). The key task is to translate the severity of (PGA) ground motion into estimates of structural damages and other economic costs. FEMA has developed a computer application (HAZUS) to give estimates of these earthquake effects.

Michigan has a comparatively low risk of experiencing damaging ground movements. Because of this low risk, however, many designers and developers did not take into consideration the possibility that an earthquake *might* occur. Some of Michigan's communities may actually be quite vulnerable to earthquake effects—especially Michigan's underground utilities—in cases where developed areas were not designed to withstand any ground movements.

Urban areas and active mineland/quarry areas may experience seismic effects as a result of blasting activities, subsidence, structural collapses, vibrations from trains and trucks, or explosions (such as from industrial accidents or terrorist activity). It is therefore worth considering a strengthening of infrastructure as well as interior design enhancements to resist both natural and other types of seismic impacts, vibrations, and stresses.

Impact on the Public

Earthquakes have the potential to cause impacts on an area's infrastructure and energy if a significant event occurs. Impacts could include higher prices for energy and supplies, and the potential for limited supplies of needed goods and resources. A major event, such as a large-scale temblor in the New Madrid Zone, may constitute a National Emergency event (on the scale of Hurricane Katrina), in which there is a need for mutual aid to be provided to states which were strongly affected, and the intake of evacuees from those states. There is a moderate potential for property damage to occur in areas of southern Michigan that are more prone to experiencing seismic activity, and these damages would clearly be inconvenient for homeowners and businesses, at the very least.

Impact on Public Confidence in State Governance

The public may perceive earthquake effects in terms of a governmental failure to plan for and maintain appropriate standards for infrastructure durability and hardening. Some questions may also be raised about whether sufficient geological research had been conducted in the area, and about whether there was a successful means of providing advance warning that the area might experience an earthquake.

Impact on Responders

Response operations have the potential to include search and rescue activities, which involve special risks and requirements for training and equipment. Earthquake-related infrastructure failures or road subsidence may inhibit efficient and safe response to the incident, and may interfere with the access and use of resources needed for normal and emergency response activities.

Impact on the Environment

A significant earthquake has the potential to cause problems for the environment, both directly and indirectly. Ground movement may disrupt wildlife habitats and change an area's landscape. Secondary environmental impacts caused by a significant event may involve a hazardous materials release into the ground, air, or water from damaged buildings and infrastructure. Fortunately, it is unlikely that an earthquake, even a significant-magnitude New Madrid event, would cause great environmental impacts in Michigan.

Programs and Initiatives

The Federal government has several programs and initiatives in place to help reduce the earthquake threat, two of which impact Michigan. The most recent, and perhaps most prominent, is the development of the National Response Framework (NRF) to coordinate federal assistance to a catastrophic earthquake or other similar disaster. Coordinated through the federal Department of Homeland Security (DHS), the NRF outlines the responsibilities of all federal agencies with a role in disaster response and/or recovery. Should a catastrophic earthquake ever impact Michigan, federal response and recovery assistance would be coordinated under the provisions set forth in the NRF.

In January 1990, Executive Order (EO) 12699, Seismic Safety of Federal and Federally Assisted or Regulated New Building Construction, was signed into law. This EO requires that appropriate seismic design and construction standards and practices be adopted for any new construction or replacement of a federal building or federally regulated building receiving federal assistance. The purpose of this EO is to reduce risks from failure of federal buildings during or after an earthquake.

Mitigation Alternatives for the Earthquake Hazard

The biggest Michigan threats would be to pipelines, buildings that are poorly designed and constructed, and shelving, furniture, mirrors, gas cylinders, etc. within structures that could fall and cause injury or personal property damage.

- Adopt and enforce appropriate building codes.
- Use of safe interior designs and furniture arrangements.
- Obtain insurance.
- "Harden" critical infrastructure systems to meet seismic design standards for "lifelines."

Tie-in with Local Hazard Mitigation Planning

Because many means of implementing mitigation actions occur through local activities, this updated MHMP places additional emphasis on the coordination of State-level planning and initiatives with those taking place at the local level. This takes two forms:

1. The provision of guidance, encouragement, and incentives to local governments by the State, to promote local plan development (including a consideration of earthquakes), and
2. The consideration of information contained in local hazard mitigation plans when developing State plans and mitigation priorities.

Regarding the first type of State-local planning coordination, the information immediately following provides advice regarding the earthquake hazard to offer guidance to local planners, officials, and emergency managers. It has been adapted from the February 2003 “Local Hazard Mitigation Planning Workbook” (EMD-PUB 207). For the second type of State-local planning coordination, a section follows that summarizes earthquake information as it has been reported in local hazard mitigation plans. For a brief summary of earthquake-related information from that section of this plan, it will here be noted that earthquakes were identified as one of the most significant hazards in the local hazard mitigation plans for Cass and Dickinson counties.

Earthquake Guidance for Local Hazard Mitigation Planning

Although earthquakes are generally not considered a major hazard in Michigan, other states have had so many problems with this hazard that very detailed techniques have been developed to estimate earthquake risks. Each area of the country has been assessed by geologists (according to types of bedrock, fault line proximity, and probably other factors) and sorted into general zones of earthquake risk. (For a national map showing this, see the web site at http://earthquake.usgs.gov/research/hazmaps/.) These zones are expressed in terms of a probability that significant ground movements will be felt. For example, there may be a 10% chance of an area experiencing significant ground movement within a 50 year period, (which is similar to the "500-year" floodplain, since the annual probability of such an event calculates as roughly .0021). The other component of risk calculation would be to estimate the amount of damage that is likely when such an event occurs. Official measures use the concept of Peak Ground Acceleration (PGA, which is also abbreviated as %g). All that remains is to translate the severity of (PGA) ground motion into estimates of structural damages and other economic costs. The earthquake analysis should use historic data to estimate the extent to which different types of structures would be affected by different severities of ground movement that are likely to regularly occur in your area. The extent of damage can then be expressed in terms of the value of the structure, its contents, and its functional and economic significance for the community. FEMA has developed a computer application (HAZUS) to give estimates of these earthquake effects.

Michigan has a comparatively low risk of experiencing damaging ground movements. Because of this low risk, however, many designers and developers did not take into consideration the possibility that an earthquake *might* occur. Some of Michigan's communities may actually be quite vulnerable to earthquake effects—especially Michigan's underground utilities—in cases where developed areas were not designed to withstand any ground movements. Detailed earthquake risk analyses in Michigan could identify facilities or infrastructure that *might* be at-risk, and then have engineers calculate the degree of actual vulnerability to those facilities. Engineers should be able to estimate potential damages and calculate structural reinforcement costs to see if earthquake mitigation measures are economically justifiable.

Urban areas and active mineland/quarry areas may experience seismic effects as a result of such things as blasting activities, subsidence, structural collapses, vibrations from trains and trucks, or explosions (such as from industrial accidents or terrorist activity). It is therefore worth considering a strengthening of infrastructure as well as interior design enhancements to resist both natural and other types of seismic impacts, vibrations, and stresses.

Modified Mercalli Intensity Scale (and Michigan map)

The map on the next page shows the worst anticipated impact upon Michigan from a major New Madrid earthquake event. The level of impact is described in terms of numeric categories along the following scale:

I – Not felt by people

II – People at rest or in tall buildings may feel movement

III – Many indoors feel movement; hanging objects swing; like the vibrations from a light truck passing by

IV – Most persons indoors feel movement, and a few persons outdoors; like the vibrations from a heavy truck passing by

V – Almost everyone feels movement; dishes break, and small unstable objects move; liquids may spill

VI – Everyone feels movement; many run outdoors; walking is difficult; breakables fall and break; plaster may crack **[NOTE: This is the worst level of severity known to potentially affect Michigan.]**

VII – Cars shake; chimneys, tiles, and plaster may fall from buildings; slight damage to well-built buildings; considerable damage to poorly built buildings

VIII – Difficulty steering cars; tall structures and chimneys may fall

IX – Well-built buildings may suffer considerable damage; houses can move off their foundations; underground pipes break

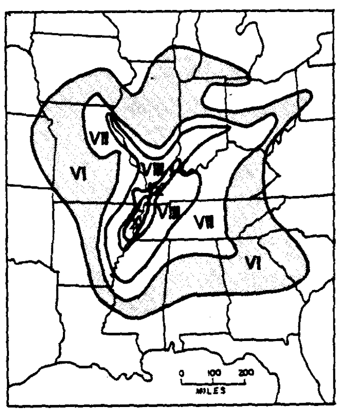
X – Most buildings and foundations are destroyed

XI – Most buildings collapse

XII – Almost everything in the area is destroyed

Earthquake Threat in Michigan

Source: U.S. Geological Survey



Regional map of maximum intensities that would result from a magnitude Ms=7.6, maximum intensity earthquake anywhere along the New Madrid Seismic Zone.

The map shows an approximate area where the worst damage might occur (Intensity VI). North of the shaded region could experience Intensity V effects. If another line is drawn, parallel to that demarcating the northern limit of the Intensity VI area, but shifted northward to include the “Thumb area” of Michigan, then that would approximate the area with Intensity V potential effects from the worst New Madrid earthquake event. Most of the rest of the state would experience a maximum of Intensity IV effects from such an event.

Subsidence

The lowering or collapse of a land surface, caused by natural or human-induced activities that erode or remove subsurface support.

Hazard Description

Subsidence is the lowering or collapse of a land surface, due to loss of subsurface support. It can be caused by a variety of natural or human-induced activities. Natural subsidence occurs when the ground collapses into underground cavities produced by the solution of limestone or other soluble materials by groundwater. Human-induced subsidence is caused principally by groundwater withdrawal, drainage of organic soils, and underground mining. In the United States, these activities have caused more than 17,000 square miles of surface subsidence, with groundwater withdrawal (10,000 square miles of subsidence) being the primary culprit. In addition, approximately 18% of the United States land surface is underlain by cavernous limestone, gypsum, salt, or marble, making the surface of these areas susceptible to collapse into sinkholes.

Generally, subsidence poses a greater risk to property than to life. Nationally, the average annual damage from all types of subsidence is conservatively estimated to be at least $125 million. The National Research Council estimate of annual damage from various types of subsidence is outlined in the table below:

Land Subsidence: Estimated Annual National Damage

Type of Subsidence	Annual Damage ($)
Drainage of organic soils	40,000,000
Underground fluid withdrawal	35,000,000
Underground mining	30,000,000
Natural compaction	10,000,000
Sinkholes	10,000,000
Hydrocompaction (collapsible soils)	N/A
TOTAL:	**$125,000,000**

Source: National Research Council; Multi-Hazard Identification and Risk Assessment, Federal Emergency Management Agency

Mine Subsidence

In Michigan, the primary cause of subsidence is underground mining. Although mine subsidence is not as significant a hazard in Michigan as in other parts of the country, many areas in Michigan are potentially vulnerable to mine subsidence hazards. Mine subsidence is a geologic hazard that can strike with little or no warning and can result in very costly damage. Mine subsidence occurs when the ground surface collapses into underground mined areas. In addition, the collapse of improperly stabilized mine openings is also a form of subsidence. About the only good thing about mine subsidence is that it generally affects very few people, unlike other natural hazards that may impact a large number of people. Mine subsidence can cause damage to buildings, disrupt underground utilities, and be a potential threat to human life. In extreme cases, mine subsidence can literally swallow whole buildings or sections of ground into sinkholes, endangering anyone that may be present at that site. Mine subsidence may take years to manifest. Examples of collapses occurring decades after mines were abandoned have been documented in several areas of the country.

Michigan's Mining Experience

Michigan's rich mining heritage has played a significant role in the State's development into a world economic power. Due to its diverse geology, Michigan has a wide variety of mineral resources, most notable of which are copper ore, iron ore, coal, sand, gravel, gypsum, salt, oil and gas. It is not surprising then that underground mining has occurred on a significant scale throughout Michigan's history. The principal types of underground mining that occurs, or has occurred in Michigan, include coal mining, metallic mineral mining, salt mining, gypsum mining, and solution mining.

Copper Mining

Copper mining, in particular, put Michigan on the map as a major mining area. Although native copper ore occurs in other parts of the world, at one time the quantity of Michigan's native ore was unsurpassed. From the mid to late 1800s, Michigan's Keweenaw Peninsula mines produced more native copper ore than any other mining area in North America. As those resources became depleted, copper mining began near White Pine in Ontonagon County. The target strata in the White Pine mining operations were on an anticline that was mined both at depths as shallow as 100 feet and as deep as 2900 feet. Over-mining of pillars in shallow parts of the mine caused collapse and subsidence at the surface, on mine property, during the 1980s. The "Copper County" area generally crosses Ontonagon, Houghton, and Keweenaw Counties.

Iron Ore Mining

Michigan's Lake Superior region has been home to significant iron ore mining operations since the mid-1800s. The iron producing areas are referred to as ranges, since the iron deposits generally occur on the slopes or at the base of remnants of ancient mountain ranges. Michigan has three ranges: 1) Gogebic Range, which extends from Gogebic County into Wisconsin; 2) Marquette Range, in Marquette County; and 3) Menominee Range, in Dickinson and Iron Counties. Most near-surface iron deposits in these three ranges have been exhausted, so underground mining has become the primary extraction technique. Nearly two billion tons of iron ore have been extracted from these areas. Unfortunately, economics have forced the closure of many of the underground iron mining operations, although one company still mines in the region. The "Iron Range" area generally includes the five counties of Baraga, Dickinson, Gogebic, Iron, and Marquette.

Salt/Solution Mining

Michigan also has one of the world's largest underground salt accumulations. The thickest salt beds lie under most of the Lower Peninsula. These formations are, in some places, over 3,000 feet thick and composed of layers of salt and other minerals. Michigan ranked first or second in national salt production from 1880 to the late 1920s. The bulk of the salt production was from natural brines pumped from six salt formations. Salt was also produced from artificial brines that were derived by injecting freshwater into salt formations and retrieving the resulting brines (called solution mining). The old Detroit salt mine produced rock salt using the "room and pillar" method until 1983. (The room and pillar method involves creating large underground expanses [rooms] in which to mine, supported by pillars [natural or artificial structural members] that held in place the roofs of these rooms.) The Detroit salt mine was approximately 1,100 feet below ground, and encompassed approximately 1,100 acres of subsurface land. The room and pillar method is being used only in the single salt mine that is still operating in Michigan, by the Detroit Salt Company, which has an excellent safety record. Salt is also being produced from brines extracted at various locations within the state.

Gypsum Mining

Gypsum has been mined in Michigan since 1841. In the Grand Rapids area, gypsum is mined by the "room and pillar" method. Open pit mining is used in the Alabaster region (Iosco County). In both of these areas, gypsum beds directly underlie thin layers of glacial drift. Closed topographic lows observed in both areas are believed to be due to groundwater solution of the gypsum and subsequent collapse of the overlying material.

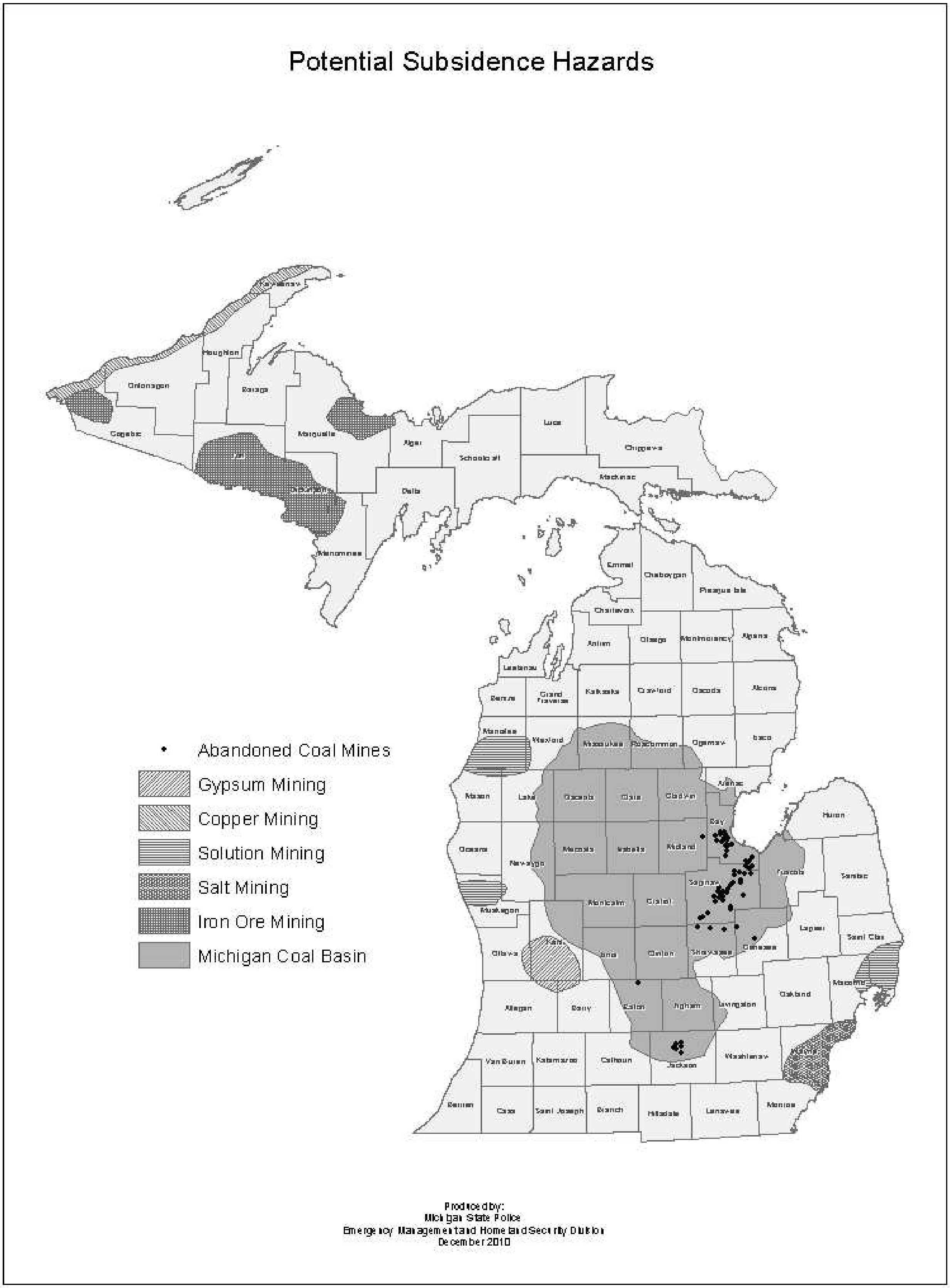
Coal Mining

Michigan also once supported a thriving coal mining industry. Records indicate that over 165 different coal mines operated in Michigan's coal-bearing region, which includes 31 counties in the south-central portion of the Lower Peninsula. Over 100 of the 165 known coal mines in the state were located in the Saginaw Bay area. (See the map on the following page for an outline of Michigan's Coal Basin.) Coal was first discovered in Michigan in 1835 in Jackson County. From that discovery, several small underground and surface coal mines were opened in that area of the state. In 1861, coal was discovered near Bay City, and in 1897 commercial coal mining began in Bay County. That led to the establishment of numerous additional mines in Saginaw, Tuscola and Genesee counties, which tended to be larger, deeper and more extensive mines. That was the start of Michigan's coal mining industry.

The state's underground coal mines were an average of 110 feet deep, and were worked by the "room and pillar" method. Michigan had continuous coal mining from 1897 to 1952, when the last underground coal mine near St. Charles, Saginaw County, closed. From 1860 (the year mine records were first kept) until 1975 (the year the last surface coal mine closed), the 165 commercial coal mines produced a total output of over 46 million tons of coal. The maximum coal output was achieved in 1907, when Michigan's 37 operating coal mines produced two million tons per year - enough to supply 16% of Michigan's then total demand for coal.

Mine-Related Subsidence Threats in Michigan

Source: Michigan Department of Environmental Quality, Office of Geological Survey



Mine Subsidence Problem in Michigan

The legacy of underground mining can be felt in numerous locations across the state. Many of the underground mining areas, whether active or abandoned, are vulnerable to subsidence in some form. The map on the previous page indicates the areas in the state that are potentially vulnerable to mine subsidence. Unfortunately, records of abandoned mines are often sketchy and sometimes non-existent. Therefore, it is often difficult to determine exactly where the mines were located. Many areas of Michigan may have developed over abandoned mines and may not even be aware of it. Oftentimes, the only way a community or home / business owner becomes aware of a potential hazard is when subsidence actually occurs and damage or destruction results.

Water-Related Subsidence

Compaction of soils in some aquifer systems can accompany excessive ground-water pumping and cause subsidence. Excessive pumping of such aquifer systems has resulted in permanent subsidence and related ground failures. In some systems, when large amounts of water are pumped, the subsoil compacts, thus reducing in size and number the open pore spaces in the soil that previously held water. This can result in a permanent reduction in the total storage capacity of the aquifer system. More than 80% of the identified subsidence in the United States is a consequence of human impact on subsurface water. Three distinct processes account for most of the water-related subsidence: compaction of aquifer systems, drainage and subsequent oxidation of organic soils, and dissolution and collapse of susceptible rocks.

Mining Ground Water

Groundwater in the pore spaces of an aquifer supports some of the weight of the overlying materials. When groundwater is depressurized or even removed from aquifers, where the materials are very compressible and pore pressures can be high, compaction may occur. This subsidence may be partially recoverable if pressures rebound, but much of it is not. Thus the aquifer is permanently reduced in capacity, and the surface of the ground may also subside. The picture on the next page shows the unconsolidated aquifer systems in Michigan

Drainage of Organic Soils

Land subsidence may occur when soils rich in organic carbon are drained for agriculture or other purposes. The most important cause of this subsidence is microbial decomposition, which, under drained conditions, readily converts organic carbon to carbon-dioxide gas and water. Compaction, desiccation, erosion by wind and water, and prescribed or accidental burning can also be significant factors. The picture on the next page shows the location of the organic soils in Michigan.

Collapsing Cavities

This type of subsidence is commonly triggered by ground-water-level declines caused by pumping and by enhanced percolation of ground water. Collapse features tend to be associated with specific rock types, such as evaporites (salt, gypsum, and anhydrite) and carbonates (limestone and dolomite). These rocks are susceptible to dissolution in water and the formation of cavities. Salt and gypsum are much more soluble than limestone, the rock type most often associated with catastrophic sinkhole formation. Evaporite rocks underlie about 35 to 40% of the United States, though in many areas they are buried at great depths. Collapse sinkholes may develop over a period of hours and cause extensive damage. The picture on the next page shows the location of the evaporite and carbonate rocks in Michigan.

Water-Related Subsidence Problems in Michigan

In the past there has been pressure for the Great Lakes states to export bulk quantities of water to various locations in the United States. If these plans to withdraw large amounts of water from the Great Lakes ever took place, it may have a major effect on the level of the ground water tables in Michigan, which may possibly make subsidence a more common occurrence. Currently, broken water pipes and the improper discharge of rainwater are the most common causes of water-related subsidence in Michigan. It most commonly occurs on sandy or silty ground when the water from the leak washes out the fine particles beneath the foundation, causing voids that result in collapse or subsidence.

Water-Related Subsidence Threats in Michigan

Unconsolidated Aquifer Systems

Organic Soils

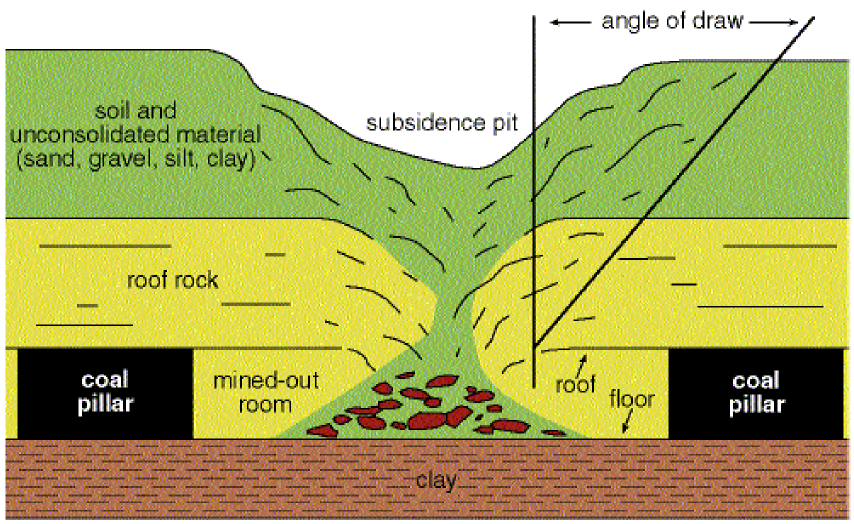
Evaporite and Carbonate Rocks

Source*:* U.S. Geological Survey, *Ground Water and the Rural Homeowner, Pamphlet, 1982*

Overall, subsidence is not a very well-known hazard in most parts of Michigan, although it occurs with some regularity in parts of the state that have experienced past underground mining activity. The impacts of subsidence in Michigan tend to be limited in scope to individual sites and structures. Unlike some other areas in the country, such as Illinois, Ohio, Kentucky, West Virginia, Florida, Louisiana, and Pennsylvania, where subsidence is a serious concern, Michigan does not devote a great deal of state resources to the problem. Subsidence simply does not have the widespread impact potential of other natural and technological hazards that are prevalent in the state.

Underground mining has, in some respects, proved to be a double-edged sword for Michigan. On the one hand, it has fueled tremendous economic growth in many parts of the state, providing hundreds of thousands of jobs through direct mining or related industrial production activities. Mining helped put Michigan on the map as a world economic power, and even today it continues to be a major economic activity in some areas of the state. On the other hand, underground mining has also left a legacy of subsidence or threat of subsidence in some parts of Michigan. Old abandoned mines eventually begin to collapse under their own weight or human neglect, and oftentimes they swallow up whatever is built upon them. The following pictures show typical mine subsidence cross sections.

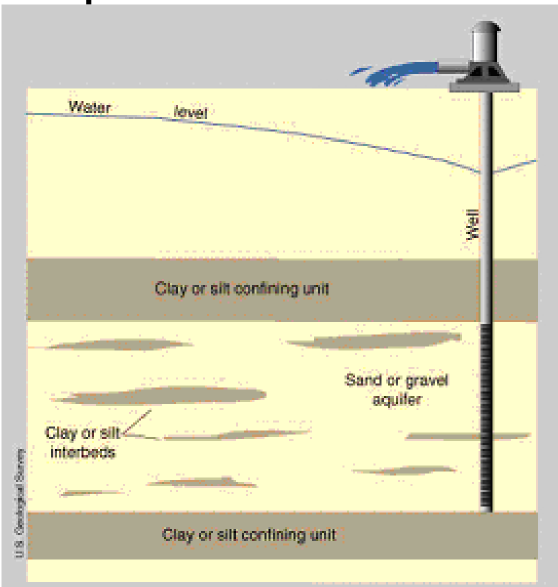
Typical Mine Subsidence Cross Section



Diagrammatic cross section of typical subsidence resulting from mine-roof collapse. No scale implied.

Source: State of Ohio, Department of Natural Resources web page

Typical Aquifer Subsidence Cross Section



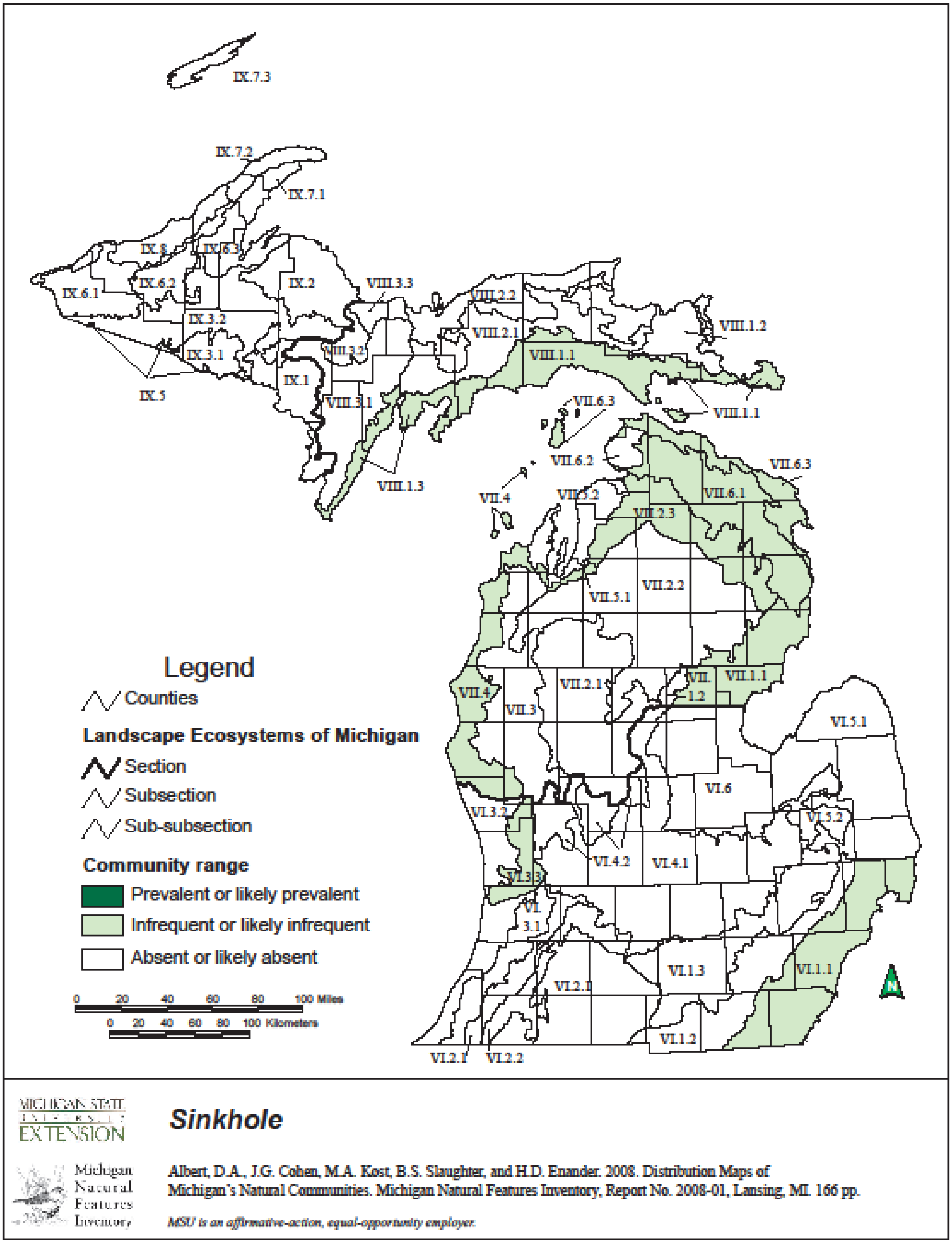
Source: U.S. Geological Survey

In some areas where ground-water pumping has caused subsidence, the subsidence has been stopped by switching from ground-water to surface-water supplies. If surface water is not available, then other means must be taken to reduce subsidence. Possible measures include reducing water use and determining locations for pumping and artificial recharge that will minimize subsidence. Optimization models, coupled with ground-water flow models, can be used to develop such strategies. The picture above shows a typical aquifer-related subsidence cross section.

Because subsidence tends to be a more sporadic hazard, and because it poses a greater hazard to property than to life, it does not receive much attention from government agencies or the public. Other natural hazards, such as tornadoes, floods and severe storms receive much more attention because of their more widespread and severe impacts. However, subsidence will continue to be a hazard that a segment of the Michigan population will have to deal with in the future. Major incidents that lead to catastrophic damage are nearly unknown in Michigan, but smaller incidents occur with some regularity in old mining areas. Overall, about four moderate incidents per decade have been noted.

Probably the most effective way to mitigate subsidence hazards is through community education and awareness. Local officials in subsidence-prone areas need to be aware of their community's potential vulnerability to subsidence, and that awareness needs to be communicated to the public. Communities that have experienced mineral and water mining activity in the past, or that have ongoing mining operations, should conduct a thorough investigation of potential subsidence sites as part of their community's hazard analysis process. More often than not, local records of mining activity are the best (and sometimes only) source of information on the nature and potential extent of the problem. Local officials can use that information to make informed community development decisions so as to avoid, to the extent possible, areas potentially vulnerable to subsidence.

Ideally, information about the locations and subsurface conditions of all mines in an area would be found, and testing or inspection could then determine their stability and safety. However, the information that does exist has no guarantee of being comprehensive, and since many mines exist on private property, the owners of that property often have an interest in not allowing any mine details to be publicized (lest the information cause trespassers to be attracted to their property). MSP/EMHSD learned about valuable information that had been collected on this topic through an academic research process, but the information was not available to the general public. The information had been provided to the relevant counties as a part of their local hazard analysis process, and it was reported that the same type of information was also known to local Mine Inspectors. The best resource to consult for each local area is probably the relevant Mine Inspector for that area. Please refer to the list available at http://www.mg.mtu.edu/mine_inspectors.htm.



Map of Michigan Sinkhole Risks – from MSU Extension
http://mnfi.anr.msu.edu/communities/community.cfm?id=10707

Impact on the Public

Although some incidents may cause private property damage and casualties, others may affect roadways or other public infrastructure, and thus cause a more general impact on the population of an area. (Please refer to the infrastructure failures subsection.)

Impact on Public Confidence in State Governance

The public may be prone to overestimate the amount of knowledge possessed by State government regarding areas and specific locations in which historic mines have existed. Subsidence events that involve damage to infrastructure or roadways may be attributed to poor maintenance or funding, rather than to the actual cause of subsidence that was responsible. Uncertainty about the extent of risk from subsidence may cause collective dissatisfaction with the area in which the hazard is present (or perceived to be present), and (at an extreme) may lower property values and cause or exacerbate emigration from the area.

Impact on Responders

Special hazards may be present in old mines or ground subsidence areas, which may present a risk of further collapses during emergency response. Areas that involve deep spaces, into which personnel and equipment may fall, necessarily entail a more complicated and dangerous situation for responders. Old mining tunnels may also contain toxic gases (as referred to in the oil and gas well subsections of this document).

Impact on the Environment

Environmental impacts stemming from subsidence are somewhat similar to those caused by an earthquake. Changes in an area's landscape, wildlife habitat and the natural ecosystem can all result from a sudden depression in the Earth's surface. In a severe event, infrastructure may be damaged and could release toxins into the air, soil, or waterways.

Significant Subsidence Incidents

Fortunately, Michigan has not had a catastrophic subsidence incident that involved death, injury or widespread property damage. However, smaller subsidence incidents have occurred that involved a single site or structure. The following incidents led to the implementation of reclamation projects designed to mitigate subsidence impacts. (Pertinent out-of-state incidents are also discussed.)

Various dates - U.S. Coastal States

In Florida, Louisiana, and some other coastal states, subsidence occurs with regularity, but for different reasons than it occurs in Michigan and other mining states. In Florida, subsidence is caused primarily by reductions in the water table caused by land development and groundwater withdrawal. Florida's cavernous limestone geology also plays a major role in its subsidence problem. A good example of that problem occurred on May 8-9, 1981 in Winter Park, Florida, when land collapsed, over a 36-hour period, into a sinkhole 324 feet wide and 100 feet deep. The collapse was caused in part by a prevailing drought. Damage was estimated at over $2 million and included a house, several cars, portions of several businesses, streets, and a municipal swimming pool. In Louisiana, subsidence is usually the result of a combination of oil and gas extraction, salt-water intrusion, and soil consolidation. Other coastal states face similar subsidence problems.

October 1984 - Jackson County

In October 1984, the abandoned Andrews Street Coal Mine in Jackson County partially collapsed, causing a detached garage, driveway and vehicle at a residence to collapse into a shallow sinkhole. A $12,000 emergency reclamation project was instituted in that subsidence incident.

October 1985 - Huron County

In October 1985, a subsidence incident occurred in Huron County that resulted in a sinkhole that swallowed up a portion of roadway. A $15,000 emergency reclamation project was instituted to mitigate the cause of the collapse.

May 1987 - Saginaw County

In May 1987, a subsidence incident in Saginaw County caused an attached garage and breezeway on a house to drop down several inches, damaging both structures. A $35,000 emergency reclamation project helped to mitigate the threat of future subsidence at that site.

March 1995 - Guernsey County, Ohio

In some other states around the country, subsidence has been a much more significant problem. For example, coal mining states such as Illinois, Kentucky, West Virginia, and Pennsylvania have large areas that are vulnerable to mine subsidence. In our neighboring state of Ohio, mine subsidence led to the collapse of a portion of Interstate 70 in Guernsey County in March 1995. That subsidence incident and the ensuing repair work closed the eastbound and westbound lanes of I-70 (a major national east-west highway) for several months, and final repair costs were $3.8 million. Fortunately, no deaths or injuries occurred as a result of the roadway collapse.

June 1999 - Philadelphia, Pennsylvania

Another dimension of the subsidence problem came to light in early June 1999 in Philadelphia, Pennsylvania, when several rowhouses were evacuated and torn down because they were sinking into the ground and in danger of collapsing. The homes had been built in the 1920s on old creek beds filled with a 21-foot layer of ash and cinders. Over time, the ground under the homes had slowly subsided, but then accelerated to the point where structural collapse was a real possibility. Officials suspect that sewer work done in the area in 1996 may have exacerbated and accelerated the problem. State assistance was provided to the evacuated homeowners to help offset the loss of their homes. (Homeowners insurance policies generally do not cover subsidence-related problems.) In 1987, the City had paid another $20 million to reimburse losses to 1,000 homeowners whose homes were also found to be sinking into the ground.

Although this problem occurred in Pennsylvania, it has implications for Michigan and other states. Building homes and businesses over streambeds and floodplains was a standard practice across the country during the early part of the 20th century. Home construction was lightly regulated during that period, and the regulations that were enforced were generally targeted more toward fire safety or other health and sanitation concerns. Hundreds of thousands of homes and businesses across the country may have been built in these unstable areas. Local building records are often incomplete or non-existent, so the situation may not become evident until a home or business begins to sink into the ground.

June 1999 - Milan (Monroe County)

On June 29, 1999 northbound traffic on U.S.-23 at Milan was diverted for approximately 10 hours after the pavement sank eight inches over a 30-foot stretch of highway. The subsidence and traffic diversion caused traffic to back up for several miles throughout the day. Although a definitive cause of the subsidence was not established, officials believe a leaking storm sewer may have contributed to the problem.

July 1999 - Iron Mountain (Dickinson County)

On July 27, 1999 an abandoned mineshaft in Iron Mountain (Dickinson County) caved in, exposing a 50-foot diameter by 1,600-foot deep shaft. The cave-in occurred directly adjacent to the Cornish Pumping Engine and Mining Museum, a popular tourist attraction in the downtown area. The structure was in danger of collapsing into the opening until temporary stabilization measures were taken. Officials were also concerned that further subsidence could have damaged nearby infrastructure, including a roadway. Because the cave-in posed a significant threat to public safety, a Governor's Emergency Declaration was granted to provide state assistance in securing the site and permanently capping the opening.

February 2000 – Detroit (Wayne County)

On February 9, 2000 a 15-foot sinkhole opened up on Seneca near Mack, on Detroit's east side. The sinkhole swallowed up a half-ton pickup truck. Fortunately, the truck's two occupants escaped serious injury. Officials believe a leaking underground pipe may have caused the subsidence.

April 2001 – Gaastra (Iron County)

On April 19, 2001 the City of Gaastra in Iron County sustained a cave-in of 3,360 cubic yards of soil at the abandoned Baltic Mine Pit in the city, leaving four feet of ground between the mine pit and the City's main (and only) sewer line to the wastewater treatment plant. (When the sewer line was installed in 1984, there were 100 feet of ground between the line and the edge of the pit. From 1984 to 2001, the annual recession rate at the site was nearly six feet per year.) The April 2001 cave-in was the second major subsidence incident at that site in recent months, following on the heels of a similar cave-in that occurred in August 2000. Local and state officials feared that another subsidence incident at the site could cause the sewer line to break, resulting in significant public health, safety and environmental concerns due to lack of sewer service, contamination of nearby water wells, and contamination of the Iron River. In addition, a major subsidence incident could also have caused a partial collapse of County Road 424 (which runs parallel to the sewer line), negatively impacting the area's residents and tourist-oriented businesses.

To mitigate further damage to the threatened sewer line, the City of Gaastra applied for a Hazard Mitigation Grant Program (HMGP) grant to relocate the line outside the subsidence area. Work on that project was successfully completed, including appropriate steps to stabilize the roadway shoulder and prevent further ground collapse.

March 2004 - Detroit (Wayne County)

On March 25, 2004 a sinkhole about 20 feet wide and 14 feet deep opened in the westbound lanes of Six Mile Road. It was determined that water main work done in the area in the previous six months had not been completed properly. Leaking water apparently washed away the soil underneath and created the sinkhole.

August 2004 - Sterling Heights (Macomb County)

On August 22, 2004 a sewer line break caused a section of 15 Mile Road in Sterling Heights to collapse, prompting residents in six homes to evacuate and the street to close for several weeks. After the break, two sinkholes formed and eventually merged, forming one hole 150 long and 45 feet wide There were about 15 homes in the area that lost water service for several hours and around 1,000 Detroit Edison customers lost power because utility poles were being removed for excavations to reach the sewer. About 7 million gallons of raw sewage was diverted daily from the collapsed sewer into the Mount Clemens sewage treatment plant to prevent wastewater from entering basements or polluting county drains and streams. Eight families living on the edge of the sinkhole tried to claim $1 million each for damages to their homes and for health reasons. No outcome had been reached at the time of this writing.

May 20, 2010 – Detroit (Wayne County)

A sinkhole large enough to swallow a car appeared on May 20, 2010 in downtown Detroit and closed West Lafayette Street between Shelby and Griswald. The street began to crumble away after crews working to demolish the historic Lafayette Building punctured a water line.

October 4, 2010 – Stephenson (Menominee County)

A 600-foot long crevice suddenly opened up—in some places only a foot wide and a few inches deep, but in other places more than 2 feet wide and 5 feet deep. Fortunately, this took place in an undeveloped area on private property, where no injuries were caused and no damage to built property or physical infrastructure was reported. Vibrations were felt by nearly residents, who were uncertain whether they were feeling the effects of explosive blasting or some other force. Although this event resulted in no harm, the executive director of the Delta Conservation District (in Gladstone) was quoted in newspaper reports as stating that this type of phenomenon is not unusual in the Upper Peninsula. He stated that the cause of the fissure sounded like it was the result of rock fracturing below the surface—that areas containing fractured rock formations can result in fissures and sinkholes as the result of pressures generated by the annual freeze-thaw process (and that the same process could also form hills)

January 21, 2011 – Detroit (Wayne County)

A Detroit man was injured when the front end of his SUV went into a 10-foot-wide sinkhole caused by a water main break on Detroit's west side. The 52-year-old victim was taken to a local hospital, where he was treated for minor injuries. The sinkhole was on Pickford Street between Heyden and Vaughan.

August 18, 2011 – Detroit (Wayne County)

Another serious incident occurred in Detroit, this time on Beaubien between Chandler and Smith, when a partially collapsed sewer caused a massive sinkhole to appear in the street. An SUV driving over that part of the street was the last stress that the buckling pavement could take, and the car nosedived as the road collapsed downward, shattering a water main in the process and causing the sinkhole to completely fill with water. Two women and an infant were successfully rescued from the vehicle, and some area residents were without water as the main was being repaired.

March 23, 2011 – Ann Arbor (Washtenaw County)

A crack in a concrete retention system caused a 40 foot sinkhole to occur on March 23, 2011 in Ann Arbor, outside an underground parking structure construction site. The combination of the retention wall, the thawing of the ground and sandy soils could have caused an underground cavity behind the concrete retention system to bubble up vertically to open the hole. Two businesses were closed for the day after the ground opened in a shared parking lot used by both businesses.

January 18, 2014 – Detroit (Wayne County)

A gaping sinkhole appeared in East Jefferson Avenue at Randolph Street near the Renaissance Center. It was about 8 feet wide and several feet deep, in the north lane. Sometime overnight on Saturday night or Sunday morning, January 18-19, smaller road problems had expanded into this gaping hole. It is not known whether some cars suffered damage during its formation, but the area was soon cordoned off to be worked upon by repair crews.

Programs and Initiatives

Michigan Department of Environmental Quality, Office of Geological Survey

The Michigan Department of Environmental Quality, Office of Geological Survey (MDEQ/OGS), regulates metallic mining in Michigan. The OGS regulatory authority is granted under Parts 631, 635 and 637 of the Michigan Natural Resources and Environmental Protection Act, 1994 PA 451, as amended. The Office's activities include issuing permits for metallic mining operations, maintaining maps and records on mining areas, and regulating mine reclamation. In terms of mine subsidence, the OGS works with local officials and the Office of Surface Mining Reclamation and Enforcement (OSMRE), U.S. Department of the Interior, to mitigate coal mine subsidence problems through special projects aimed at properly sealing mine shafts and otherwise ensuring the structural integrity of underground coal mined areas.

Surface Mining Control and Reclamation Act

There is very limited state funding for mine subsidence mitigation. Therefore, most of the funding for such projects comes from the federal government. The primary federal funding source is the Abandoned Mine Lands (AML) Reclamation Fund in the Surface Mining Control and Reclamation Act (SMCRA), P.L. 95-87, administered by the U.S. Department of Interior's OSMRE. AML funds are derived through a tax on coal production targeted at reclaiming land and water resources adversely affected by pre-1977 coal mining. These funds can also be used for mine subsidence mitigation measures and salt sealing, which Michigan has done on numerous occasions. Normally, priority is given to those emergency projects that involve mine lands that present an immediate danger to the public health, safety or general welfare. Typically, such emergencies include landslides near homes and across roads, subsidence occurring under houses and public buildings, mine and coal waste fires, and open mineshafts discovered near populated areas.

Subsidence Insurance

Unlike states such as Illinois, Ohio, Pennsylvania, Kentucky and West Virginia, which have state insurance programs for homes and businesses in subsidence-prone areas, Michigan does not have such a program. As a result, home and business owners and communities that are affected by subsidence must rely on whatever private insurance payments they can collect for subsidence-related damages, or they must pay for damages out-of-pocket. (Subsidence-related damage is generally not covered under a standard homeowner's insurance policy.)

National Association of Abandoned Mine Land Programs

Michigan is a member of the National Association of Abandoned Mine Land Programs, a national advocacy group that provides a forum and clearinghouse for addressing issues and problems pertaining to mine subsidence and reclamation. Michigan's participation is beneficial in that it gains tremendous knowledge of the experiences of other states in reclaiming mine sites and mitigating subsidence. In addition, Michigan also gains knowledge about current reclamation and mitigation technologies that could be applied to problem areas in the state.

Mitigation Alternatives for Subsidence

- Identifying and mapping old mining areas and geologically unstable terrain, and limiting or preventing development in high-risk areas.
- Filling or buttressing subterranean open spaces (such as abandoned mines) to discourage their collapse.
- Hydrological monitoring of groundwater levels in subsidence-prone areas.
- Insurance coverage for subsidence hazards.
- Real estate disclosure laws.

Tie-in with Local Hazard Mitigation Planning

Because many means of implementing mitigation actions occur through local activities, this updated MHMP places additional emphasis on the coordination of State-level planning and initiatives with those taking place at the local level. This takes two forms:

1. The provision of guidance, encouragement, and incentives to local governments by the State, to promote local plan development, and
2. The consideration of information contained in local hazard mitigation plans when developing State plans and mitigation priorities.

Regarding the first type of State-local planning coordination, MSP guidance has included the "Local Hazard Mitigation Planning Workbook" (EMD-PUB 207), which is currently being updated for release by 2015. For the second type of State-local planning coordination, a section later in this plan summarizes hazard priority information as it has been reported in local hazard mitigation plans. Here, it will merely be noted that subsidence was identified as one of the most significant hazards in the local hazard mitigation plans for Baraga, Dickinson, and Houghton counties.

Local Mine Inspectors

Information about the locations and subsurface conditions of mines has no guarantee of being comprehensive in an area, and since many mines exist on private property, the owners of that property often have an interest in not allowing any mine details to be publicized (lest the information cause trespassers to be attracted to their property). However, known mines are subject to inspection, to determine their stability and safety. Valuable information is available for certain counties and their local Mine Inspectors. Locally specific information should be sought from the relevant Mine Inspector for that area. Please refer to the list available at http://www.mg.mtu.edu/mine_inspectors.htm.

CELESTIAL IMPACT

An impact or threatened impact from a meteorite, asteroid, comet, satellite, space vehicle, space debris, solar storms, or similar phenomena that may cause physical damages or other disruptions.

Hazard Description

The celestial impact hazard primarily concerns the effects of large forces (from objects or energy) upon the Earth or its atmosphere. Most such forces are extraterrestrial in origin—**meteors** (which burn up in the atmosphere) or **meteorites** (which impact physically upon the ground) that were originally **asteroids** or **comets** from elsewhere in the solar system. It must be noted that even in cases where no meteorite actually strikes the ground, the explosive energies from the meteor's impact upon the many layers of atmosphere can create an intense heat and blast area, along with very strong winds, and can release more energy than even the largest nuclear bombs. Massive or fast moving bodies that impact upon either the ground, the oceans, or the atmosphere can cause widespread destruction and disruption of both human and natural systems, including secondary hazards such as earthquakes, volcanoes, tsunamis, and severe winds, although events of that magnitude are <u>extremely</u> rare.

Much more common is the flare-up of energy and charged particles that are emitted and ejected by the Sun and impact upon the Earth's atmosphere. These **solar geomagnetic storms** (also known as **space weather**) can cause widespread failures of important satellite, electronic, communication, navigation, guidance and electric power systems—which have all formed a very important part of our modern technology and lifestyles. Because of the amount and complexity of information concerning the potential impacts from space <u>objects</u>, a great deal of this section has been devoted to an explanation and analysis of that hazard. However, it is important to note at the outset that the solar storm hazard is far more likely in the near term to cause disruptive effects, large economic impacts, and risks to human life. The smaller amount of text dedicated to space weather in this document should <u>not</u> mislead readers into a sense that it is considered less important, or that it is expected to cause less impact in the near future. Rather, the conclusion of the analysis presented here is that the effects of space weather have already had, and are much more likely to have, strong impacts upon Michigan within the normal historical timeframe that is typical for this type of plan. By contrast, the extensive discussion of impacting physical objects is given primarily to be "on the safe side" so that readers and emergency managers can be well-informed in the unlikely event that a very serious incident does occur, or threaten to occur.

Although it has been estimated that a major impact from a physical body upon the Earth occurs approximately once per century, recent discoveries (and the fact that much more of the Earth has been covered by human developments within the recent past) have caused increasing concern over this hazard. Although most meteorites would be expected to strike an ocean rather than a continent, the effects of a large enough ocean strike can still be widely damaging, through resulting tsunami and seismic activities.

An important type of celestial impact involves the interference or disruption of modern electronic and communications systems, including those upon which our modern aviation networks rely. Solar flares and storms (also known as "space weather") are highly relevant for their potential impacts and possible disruption of these complex modern communication systems—satellites, television, radio, GPS, power supply networks, and the extensive human and technological infrastructure that relies upon those communication and utility networks.

Extensive evidence of previous celestial impacts upon Earth has been discovered, including evidence of a historic crater site located in southwest Michigan, but the vast majority of historical Earth impacts have had their evidence erased from normal observation by the ongoing geological processes that take place over time. Even the largest of impact sites would no longer be evident to normal observation after a period of about 200 million years (usually much, much less). Such an amount of time is less than 5% of the Earth's overall age, but it has been found that impacts used to occur much more frequently during the earlier periods in Earth's history (i.e. nearer to the period of planetary formation) than they do in recent geological periods. Clearer evidence of the many historical impacts can be seen on other celestial bodies that are less geologically active, such as Earth's own Moon.

<u>Asteroids</u>

Most asteroids are located in the main asteroid belt and have well-defined orbits there between 200 and 310 million miles from the Sun, but thousands of asteroids also exist in other parts of the solar system. There are groups of "Trojan" asteroids that share an orbit with Jupiter, for example, located 60 degrees both ahead of and behind that planet itself while going around the Sun. Asteroids that have paths which cross over Earth's orbit are classified as

Near-Earth Objects (NEOs), and are called Apollo asteroids. Two other types of NEOs are Amor asteroids, which approach the Earth's orbit from positions outside of it, and Aten asteroids, which approach the Earth's orbit from the direction of the Sun. As of January 2009, there were 6,021 NEOs identified, of which 1,026 were classified as posing the possibility of threat (having the potential to come within 466,000 miles of the Earth's orbit; by comparison, the average distance of the moon is 238,900 miles). The typical asteroid would impact upon the Earth at an angle of 45 degrees and a speed of 10 miles per second, but a wide variation around this average is possible.

Comets

More than 99% of all meteorites come from asteroids, but some comet impacts have also been confirmed (9 are known, constituting less than 0.03% of all meteorites). The main difference between comets and asteroids is that comets tend to have elliptical orbits that carry them out beyond the "nebular frost line" (located in the main asteroid belt, about 250 million miles from the Sun) and thus their composition includes a substantial amount of icy and frozen matter. Comets usually lose about 0.1% of this matter each time they pass by the sun, due to the effects of warming and the pressure of solar radiation, and this matter trails behind them in their long "tails," which include charged particles (with associated magnetic fields) and can stretch across many tens of millions of miles of space. Where such tails cross the Earth's orbit, this matter (typically small and harmless to us) generates sometimes spectacular "meteor showers" as it periodically burns up in the Earth's atmosphere at regular times during the year. After a certain number of orbits, however, the comet simply breaks apart. Even if less dense than the average asteroid, a comet's heavy nucleus can be sizeable (from several hundred meters to over 40km in diameter), and a comet impact upon the Earth would typically occur at a speed of 31 miles per second—about three times as fast as the average asteroid, with a proportionally larger momentum of destructive energy if the amount of mass is the same. (It is worth noting here that the maximum impact upon the Earth for any object orbiting the Sun would be no more than 44.5 miles per second—160,000 miles per hour.)

Comets are classifiable by their orbital period, with long period comets taking more than 200 years to travel around the Sun, and short period comets taking less than that. The short period comets are further subdivided into Halley-type comets with orbital periods between 30 and 200 years, and Jupiter-type comets with orbital periods of less than 30 years. Long period comets originate in the farthest reaches of the Solar System (the Oort Cloud) and approach the Sun and Earth from every direction, while short period comets originate from the "Kuiper Belt" that exists beyond Neptune and is approximately in the same plane as all of the major planets. Short period comets thus would approach us from more predictable, shallow angles. The comet only begins to glow, though, when it approaches to within 3 and 5 Earth-distances from the Sun (3 to 5 astronomical units). Since short-period comets tend to last for only a matter of hundreds or perhaps thousands of orbits, their number seems to be replenished by a reservoir in our solar system (whose orbits eventually become shifted by gravitational perturbations). The Oort Cloud probably contains about a trillion comets, but most of these remain so far away that we remain unaware of them. The Kuiper Belt contains billions of comets, and the average diameter of one that comes near to the Sun is about 10 km.

If advance notice of an approaching meteor, asteroid, or comet is available, then widespread alerts might be prompted by this information, much as the explosive breakup of the Space Shuttle Columbia in 2003 had required warnings and alerts across multiple southwestern states, due to the possibility of persons and property being affected by falling debris. (See the event descriptions that appear later in this chapter.) In the case of the Cosmos 954 and Space Shuttle incidents, such debris needed special handling, both for purposes of investigation and out of concern for personal safety, since some of it could have contained hazardous substances. The threat of a celestial impact could be much more dangerous and far-reaching. One clear example of the potential damage was seen in the impact of the comet Shoemaker-Levy 9 on the planet Jupiter, in 1994, which resulted in blasts that were estimated as the equivalent of ten million megatons of explosives. In comparison, the 1979 Mount St. Helens eruption was roughly 5 megatons, and the 1885 Krakatoa eruption in Indonesia was about 100 megatons. Following the Shoemaker-Levy comet impact, Congress authorized new research to analyze this type of celestial impact hazard.

Space Weather

The Sun does not "burn" in the sense that we usually experience that common heat-generating process on Earth, but rather emits huge amounts of energy from the continuous processes of nuclear fusion that take place in the Sun's core. The gravitational pressures of the Sun's enormous mass, pulling toward itself, are thus generally offset by outward pressures from the fusion processes that take place at its core. Enormous amounts of energy are radiated from the Sun, including the spectrum of electromagnetic waves up through gamma wave frequencies. These include infrared (heat) radiation, ultraviolet, all colors of visible light, x-rays, microwaves, and radio waves. The intensity of these forms of radiation varies, and gamma waves are normally only emitted during solar flare events (to be explained shortly). It should also be understood that in the midst of all these solar interactions of matter and energy are powerful magnetic forces, which also affect the distribution of heat energy in and around the Sun and sometimes cause cooler areas, called **sunspots**, to form for a while, readily visible even with crude forms of observational equipment. (Although an observer should never look directly at the Sun, a pinprick of solar light projected onto a surface provides one basic means of seeing a Solar image). The relatively low temperatures of sunspot areas, however, are coupled with a rise in energy above the Sun's surface. **Solar prominences** are arches of plasma that soar above the Sun's surface, in a pattern that is itself shaped by the powerful magnetic fields present. In some cases, these magnetic fields have become too twisted to maintain such forces within these ordinary patterns, and a **solar flare** is generated, which releases a huge amount of energy from the Sun. Normally, a **solar wind** exists in the form of milder pressures exerted by emitted photons, ions, and other particles that flow outward from the Sun until they are eventually halted (beyond the orbit of Neptune, at an area called the heliopause) by the pressure of interstellar gases. Within the realm of the Sun's planets, however, the solar wind is an ongoing feature of the space environment, constantly sending energy and charged particles outward.

Space weather is a term that denotes the impacts of the Sun's activity upon the bodies within this sphere inside the heliopause, including our own Earth. As with the weather on Earth, there are some clear patterns that are exhibited by space weather. More turbulent space weather is produced during times when more sunspots are present (called a solar maximum), and space weather is calm during times when sunspots are rare and small (or not even seen to be present at all, called a solar minimum). A **sunspot cycle** exists, in which sunspot activity regularly shifts between a minimum and maximum level. As with our Earthly seasons, however, it cannot be known in advance exactly how turbulent or calm things will be at a given moment during the sunspot cycle—only that calmer periods regularly give way to more turbulent periods. As to the regularity of the sunspot cycle itself, although it has been found that the average amount of time between a solar minimum and a solar maximum is about 11 years, the actual length varies quite a bit within each cycle. The interval is sometimes as long as 15 years and sometimes as short as 7 years. In addition, it has been observed that long periods can occur with little or no sunspot activity. The "Maunder minimum," which occurred between the years 1645 and 1715, is the primary example of such long-term variation from the normal cycle, but it is not yet known what caused it, or when it might recur. The Earth's atmosphere serves as a shield for us against many types of particles and radiation zipping across space, and Earth also has a **magnetosphere** that similarly provides protection against most of the charged particles traveling through space. There are some weak spots in the Earth's magnetic field, however, that exist near its two magnetic poles and allow many ions to penetrate, where they collide with atoms in the Earth's upper atmosphere and glow to produce the beautiful auroras in the skies of the arctic regions of the north and south. In addition, the Earth is surrounded by "belts" of charged particles (called Van Allen belts) which are hazardous to spacecraft and astronauts. These are known and predictable conditions of calm space weather, however, and the actual hazard is the turbulence that is generated by large solar flares, causing problems with radio communications, damage to satellites, and even disruptions in power delivery networks on the Earth. Currently, as of early 2012, sunspot cycle number 24 is proceeding, from a solar minimum that was reached in December 2008 and is projected to transition to a solar maximum by early 2013 (a relatively short cycle).

Another type of solar disturbance is a **coronal mass ejection** (CME), in which built-up pressures cause a sudden burst in gases and magnetic fields at tremendous speeds, with impacts that reach far across interplanetary space. Like solar flares, CME events are a cause of geomagnetic storm events on Earth (usually 1 to 4 days after the solar event), and they occur more frequently during periods with more sunspots. One of the additional effects of space weather involves increased exposure to ionizing radiation (e.g. x-rays), especially among those in aircraft at high altitudes and along polar flight paths. Extra costs, in fuel and delays, are imposed upon airlines during periods of harmful space weather.

Hazard Analysis

A couple of scales have been developed to numerically summarize the extent of risk associated with extraterrestrial celestial bodies, such as comets, asteroids, and meteoroids. One scale is called the Palermo scale, but since that is tricky to interpret, the Torino Scale has instead been featured in media reports since its initial presentation at a United Nations conference in 1995, and it was adopted by the International Astronomical Union in 1999. Both scales take into consideration the amount of destructive energy that an impact could cause, and the probability of such an impact occurring. It is common for newly discovered objects to have their initial classifications on these scales subsequently downgraded, as additional information is collected that more precisely defines the exact path of the object. In other words, an object that is initially classified as having the potential for impact, and thus being worthy of closer study, is often later reclassified as additional information reveals that little or no significant impact potential exists. The lower numbers on the scale should not be interpreted as indicating any particular concern, and in the previous 15 years, only one object (99942 Apophis) had temporarily been classified as high as a 4 on the Torino scale. Being an asteroid large enough to cause regional devastation if it struck, Apophis had initially been estimated to have a 1 in 45,000 chance of striking the Earth on April 13, 2036, but as more information was obtained about its trajectory, that estimate was downgraded to only a 4 in 1 million probability. Although the asteroid's approach will be spectacular to observe, it is predicted to come as close as 18,300 miles away from the Earth's surface as it passes. (In Celestial terms, this is a very near miss, because that distance is smaller than the circumference of the Earth.)

The official explanation of Torino Scale ratings are provided below. In addition to numerical categories from 0 to 10, the scale is also color-coded in five categories, from white to red.

THE TORINO IMPACT HAZARD SCALE:

No Hazard (White Zone)

0: The likelihood of a collision is zero, or is so low as to be effectively zero. Also applies to small objects such as meteors and bodies that burn up in the atmosphere as well as infrequent meteorite falls that rarely cause damage.

Normal (Green Zone)

1: A routine discovery in which a pass near the Earth is predicted that poses no unusual level of danger. Current calculations show the chance of collision is extremely unlikely with no cause for public attention or public concern. New telescopic observations very likely will lead to re-assignment to Level 0.

Meriting Attention by Astronomers (Yellow Zone)

2: A discovery, which may become routine with expanded searches, of an object making a somewhat close but not highly unusual pass near the Earth. While meriting attention by astronomers, there is no cause for public attention or public concern as an actual collision is very unlikely. New telescopic observations very likely will lead to re-assignment to Level 0.

3: A close encounter, meriting attention by astronomers. Current calculations give a 1% or greater chance of collision capable of localized destruction. Most likely, new telescopic observations will lead to re-assignment to Level 0. Attention by public and by public officials is merited if the encounter is less than a decade away.

4: A close encounter, meriting attention by astronomers. Current calculations give a 1% or greater chance of collision capable of regional devastation. Most likely, new telescopic observations will lead to re-assignment to Level 0. Attention by public and by public officials is merited if the encounter is less than a decade away.

Threatening (Orange Zone)

5: A close encounter posing a serious but still uncertain threat of regional devastation. Critical attention by astronomers is needed to determine conclusively whether or not a collision will occur. If the encounter is less than a decade away, governmental contingency planning may be warranted.

6: A close encounter by a large object posing a serious but still uncertain threat of a global catastrophe. Critical attention by astronomers is needed to determine conclusively whether or not a collision will occur. If the encounter is less than three decades away, governmental contingency planning may be warranted.

7: A very close encounter by a large object, which if occurring this century, poses an unprecedented but still uncertain threat of a global catastrophe. For such a threat in this century, international contingency planning is warranted, especially to determine urgently and conclusively whether or not a collision will occur.

Certain Collisions (Red Zone)

8: A collision is certain, capable of causing localized destruction for an impact over land or possibly a tsunami if close offshore. Such events occur on average between once per 50 years and once per several 1000 years.

9: A collision is certain, capable of causing unprecedented regional devastation for a land impact or the threat of a major tsunami for an ocean impact. Such events occur on average between once per 10,000 years and once per 100,000 years.

10: A collision is certain, capable of causing global climatic catastrophe that may threaten the future of civilization as we know it, whether impacting land or ocean. Such events occur on average once per 100,000 years, or less often.

Note: This is the Torino Scale as revised in 2005. A graphic of the Torino Scale is also available at http://neo.jpl.nasa.gov/images/torino_scale.jpg .

The Palermo Technical Impact Hazard Scale is a bit different, with values less than -2 reflecting events for which no consequences are likely, values between -2 and 0 indicating situations that merit careful monitoring, and values above zero indicating situations that merit some level of concern. This document presents only the Torino scale in its entirety, since that scale was developed for general public informational uses.

About 40,000 to 60,000 tons of extraterrestrial material falls onto the Earth each year, but most of it is mere dust. Larger materials fall during regular cycles called meteor showers, but again most of it is small enough to harmlessly burn up (through ablation) as it hits the Earth's atmosphere at high speeds (typically about 67,000 mph). During meteor showers, the material is typically leftover debris from comets that had crossed the Earth's orbit, and most such material is very small and harmless to us. Material that does survive ablation to strike the Earth's surface lands in random locations, and since 70% of the Earth's surface is water, these meteorites mostly go unnoticed by ordinary people. The risk to Michigan is calculable in general terms, by considering the proportion of the Earth's total surface area that is occupied by Michigan's land area. This is approximately 2.9×10^{-4}, or 0.00029. The frequency of global impact events can then be multiplied by this factor to estimate the frequency of impact events directly upon Michigan's land area. This results in the following estimates, on average, for different sizes of impacts upon Michigan's land itself:

- About 1 to 5 impacts per year that are larger than 100g (golf-ball size) – This may kill an individual that is struck, but since most space is not occupied by a person at any particular moment, such a thing is exceptionally rare, and there have only been a couple of confirmed meteorite injuries worldwide. Instead, such incidents are more likely to simply cause limited property damage to a car or home, although their appearance in the sky can appear impressive and be accompanied by a sonic boom. (Example: the Washtenaw County strike of 1997.)
- About one impact per century involving an object of more than 100kg (220 pounds), and about one impact every 1700 years involving an object of more than 1000kg (about 2200 pounds) – These types of events would result in loud sounds and bright flare-ups in the sky, leaving a field of fragments strewn across an area that is miles across, but actual damages are likely to be only moderate unless a dense urban area or critical facility happens to be struck. (Example: the Park Forest, IL event of 2003.)
- About one impact every 350,000 years involving an object of more than 100,000kg (about 220,000 pounds) – This is the type of impact that resembles an atomic blast, exploding brightly in the sky and producing a very strong blast wave and severe winds that would cause extensive building damages and collapse at ground level, and would flatten forest lands. (Example: the Tunguska, USSR event of 1908.)

Although that last type of event is so rare that it need not be of general concern for Michigan, the probability of such an event affecting some part of the U.S. and potentially causing a national emergency is a bit larger, but still remote. It is most probable that the next such event will occur elsewhere in the world (on the order of about 1 event per century) and, although potentially devastating to that area, Michigan's role would probably only involve the voluntary donation of humanitarian aid to the disaster area. One foreseeable scenario could involve an asteroid impact in the ocean, which causes tsunami impacts upon the associated coastline of the U.S.—waves could be more than 100 feet high from the impact of an asteroid with a diameter of 1300 feet, although that scale of event would only be expected about once in 80,000 years. These types of large events—the kind that would actually form sizeable craters and cause catastrophic national or global impacts (including major seismic and volcanic effects and global cooling from gaseous effects and dust, smoke, and particulates deposited into the atmosphere)—are rare enough that no extensive description will be provided here—past events of that type are well-established in a geological timeframe but not in a human historical timeframe. (Reference will be made to such events primarily in the description of mitigation strategies.)

Since meteors flare up brightly in the sky, some persons have speculated about whether meteorites could then cause wildfires to start up. As it turns out, this is generally not the case. The flaring fireballs are caused by ablation, as the very fast meteors encounter the atmosphere and friction generates heat, but a great amount of material typically burns away in this process, followed by miles of additional falling before ground impact, during which time the contact with blowing air exerts a cooling effect. The vast majority of meteorites are actually cool when they strike the ground. It would take a very large impact to bring a degree of heat that is capable of igniting a forest fire, and impacts of that size are very rare. That type of rare, large impact would also tend to flatten forest lands at the same time, with blast pressure and wind effects that could offset much of the fire risk. A large (Tunguska-sized) event would cause forest fires, along with huge amounts of other damage, and it is conceivable that a smaller-sized (but still very rare) impact might cause wildfire ignition if there are already drought conditions present that have increased the natural wildfire risk. In general, wildfires will not be caused by meteorites, and there is no good evidence that any of Michigan's historic wildfires were of meteoritic origin.

Space weather can be very expensive for those who use or rely upon satellites. During a solar maximum, the Earth's upper atmosphere expands and increases the drag upon satellites within low orbits, which will then require boosting in order to remain aloft. Electronic circuits can malfunction and cause interruptions or complete losses in operational capacity. Space missions may also need to be delayed, in order to ensure their safety and success. Special design features may require additional expenses, to mitigate the effects of space weather. Communication disruptions can inhibit navigation and hinder the safe management of air and sea traffic. Electric currents are induced by the relative motion of magnetized material, and these can affect power supply and pipeline infrastructure, potentially causing weakening and damage in these systems as well as electronic malfunctions. Three space weather scales are in use by NOAA/NWS to summarize the intensity and potential impact of three different types of space weather effects. Each uses a 5-category classification scheme, and the three scales denote (1) geomagnetic storm intensity, on a G-scale, (2) solar radiation storms, on an S-scale, and (3) radio blackouts, on an R-scale. Weaker events are given a number of 1 on the scale, and extreme events are rated as a 5. In this document, selected material is summarized below. For more detailed information, please refer to the NOAA web site at http://www.swpc.noaa.gov/NOAAscales/.

NOAA Space Weather Scales

NOTE: Each type of space weather may occur separately. Descriptions of all three types of space weather warnings are here combined into one table merely to conserve space.

HF means high frequency (radio waves), but other radio frequencies may also be affected by these events. LF means low frequency (radio waves). F: refers to event frequency.

Category Labels	Geomagnetic Storms (effect & frequency)	Solar Radiation Storms (effect & frequency)	Radio Blackouts (effect & frequency)
Minor G1 S1 R1	G1 events can cause weak power grid fluctuations, minor impacts on satellite operations, effects on migratory animals, and widely visible auroras seen in Northern Michigan. F: about 900 days per solar cycle.	S1 events result in minor impacts on HF radio in polar regions. F: about 50 such events per solar cycle, each of which can last more than 1 day.	R1 events cause weak or minor degradation of HF radio communication on the sunlit side of Earth, and occasional loss of radio contact. LF navigation signals used by maritime and general aviation systems may be degraded for brief intervals. F: about 950 days per solar cycle.
Moderate G2 S2 R2	G2 events can cause high-latitude power systems to experience voltage alarms. Long-duration storms may cause transformer damage. Corrections to satellite orientation and orbital drag prediction may be required. HF radio propagation can fade at higher latitudes. Auroras may be visible throughout Michigan. F: about 360 days per solar cycle.	S2 events may expose persons in high-flying aircraft to an elevated radiation risk* in areas of high latitude. Infrequent single-event upsets of satellite operations are possible. Possible effects on HF propagation and navigation through polar regions. F: about 25 events per solar cycle, each of which can last more than 1 day.	R2 events cause a limited blackout of HF radio communications on the sunlit side of Earth, and loss of radio contact for tens of minutes. LF navigation signals may also be degraded for tens of minutes. F: about 300 days per solar cycle.
Strong G3 S3 R3	G3 events may require voltage corrections at power systems and may trigger false alarms on their protection devices. Satellite orientation problems may need correction. Increased atmospheric drag and component surface charging may occur. Intermittent LF radio navigation problems may occur. F: 130 days per solar cycle.	S3 events can expose persons in high-flying aircraft to a radiation risk* in areas of high latitude. Satellite operations may experience single-event upsets, imaging system noise, and slight solar panel inefficiencies. Degraded HF radio propagation in polar regions. Navigation position errors are likely. F: about 10 events per cycle (each can exceed 1 day).	R3 events cause a wide area blackout of HF radio communication and loss of radio contact for about an hour on the sunlit side of Earth. LF navigation signals may be degraded for about an hour. F: about 140 days per solar cycle.
Severe G4 S4 R4	G4 events may cause widespread voltage control problems for power systems, and mistaken exclusion of key assets from a power grid by some protective systems. Satellites may experience surface charging, tracking and orientation problems that may need correction. Pipelines may experience induced currents. HF radio propagation sporadic. LF radio disrupted. Satellite-based navigation may be degraded for hours. F: about 60 days per solar cycle.	S4 events can expose persons in high-flying aircraft to a radiation risk* in areas of high latitude. Satellites may experience memory device problems, imaging systems noise, orientation problems, and degraded solar panel efficiency. A blackout of HF radio communications is likely through the polar regions. Increased navigation errors over several days are likely. F: about 3 events per solar cycle (each can exceed 1 day).	R4 events cause an HF radio communication blackout on most of the sunlit side of Earth for 1 to 2 hours, with HF radio contact lost during this time. LF navigation signals cause increased errors in positioning for 1 to 2 hours. Minor disruptions of satellite navigation are possible on the sunlit side of Earth. F: about 8 days per solar cycle.
Extreme G5 S5 R5	G5 events may cause widespread voltage control and protective system problems in power systems, with some grid systems completely blacking out or collapsing, and possible damage to transformers. Satellites may experience extensive surface charging, orientation, tracking, and linkage problems. Pipelines may receive induced currents reaching hundreds of amps. HF radio may be out for 1 to 2 days in many areas. LF may be out for hours. Satellite-based navigation may be degraded for days. Bright auroral lights visible at night. F: about 4 days per solar cycle.	S5 events can expose persons in high-flying aircraft to a radiation risk* in areas of high latitude. Satellites may be rendered useless, may receive permanent solar panel damage, or may experience memory problems, loss of control, serious imaging data noise, and navigation problems. Complete HF radio communications blackouts are possible throughout the polar regions. Navigation operations will be extremely difficult and error-laden. F: less than 1 event per solar cycle should occur, although an event may exceed 1 day in duration.	R5 events cause a complete HF radio blackout on the entire sunlit side of Earth for a number of hours. No HF radio contact with mariners and aviators in this sector. LF navigation signals experience outages for many hours on the sunlit side of Earth, causing loss in positioning. Satellite navigation errors in positioning increase for several hours on the sunlit side and may spread into the night side of the Earth. F: fewer than 1 event per cycle.

*** Pregnant women are particularly susceptible to radiation risk.**

Meteors are commonly observed, illuminating briefly in the sky as the force of friction with the Earth's atmosphere burns away the solid matter they contain. Some meteors partially survive this process and thus become meteorites by striking the Earth's surface and potentially causing great amounts of damage. However, there are cases in which huge fiery blasts occurred in the sky (bolides) without any meteorite remnants being found. Enormous damage can still occur at ground level from the effects of the heat, blast force, and strong winds that result from the atmospheric impact (see the description provided for the 1908 event at Tunguska, Russia, later in this section). In addition, the effects of the sonic boom and blast wave from a less severe event, such as the one at Chelyabinsk in February of 2014, has been seen to be widely damaging to urban areas, because of the large amount of glass that is used in built structures.

Part of the usefulness of this analysis is meant to involve the presentation of information that might alleviate confusion throughout Michigan's communities and residents, in case some event actually does occur, or should some warning of an impending impact eventually be given out. In the former case, those who already have some information about meteors, and the potentially spectacular appearance of either sky or ground impacts, would have a means to make sense of an unusual bolide or impact event and would be less likely to mistake the event for a nuclear explosion. A greater general awareness of the variety and nature of Michigan's hazards should eventually translate into a lessened demand for emergency services and information. For example, it might take only 30 seconds to explain to a knowledgeable citizen that a meteor impact caused a huge explosion in the sky (and an impact on the ground), whereas a less-knowledgeable citizen might seek 20 minutes of reassurance that the explosion was not nuclear, that the incident was not connected with a crashing airplane or a confidential military experiment, and so on. The provision of advance information that realistically describes and assesses the nature of unusually severe events can help to provide a framework in which the correct interpretation and response actions can be undertaken more quickly and efficiently.

In the latter case, involving an alert about an impending impact or potential impact, many persons would need information that allows them to understand the nature of the threat, and the techniques that may be used to prevent or mitigate its impacts. For example, there is an enormous difference between an alert that provides only a few weeks of notification, and one that has identified a need for action over the course of several decades.

It should be realized that although the atmosphere and air around us seems to be "light" and only a small obstacle to movement (mostly at high speeds or during strong wind gusts), the air nevertheless has enough substance to sustain heavy aircraft in flight, to hold aloft huge thunderstorm clouds full of rain, and so on. A meteor crashing into the atmosphere thus releases tremendous amounts of energy, as the result of friction from plunging through large quantities of air at enormous speeds. This energy can result in large (and loud) blast waves, even if the meteor's trajectory is oblique enough to cause it to "bounce off" the atmosphere, rather than plunging through it and hitting the ground. For example, if a towel is wrapped around a bowling ball, a baseball can easily be bounced off the top of the bowling ball without leaving a dent or scratch in the bowling ball's surface, but it would still make a clearly audible noise and could crush any small insect that happened to be crawling underneath the towel. The towel can be seen as an analogy for our ecosphere on the surface of the planet, and the visible results of such an atmospheric impact could include great bursts of flame, damaging shock waves, severe winds, deafening noise, and disrupted weather patterns.

While this section is not intended to focus upon planetary life-ending scenarios (which are remotely possible but extremely unlikely to occur within our lifetimes), it does consider the possibility of a major (averaging once per century) impact that may cause either an area of widespread destruction within the United States, or an impact somewhere else in the world that may cause unusual effects to be felt in distant locations. If a Tunguska sized event (see the 1908 entry in the list of Significant Events later in this section) were to affect a densely populated area, the results could be extreme enough to constitute a National Emergency. (Please refer to the new section describing "Catastrophic Incident," for more discussion about this, as well as the Nuclear Attack section, for more information about problems such as mass fires, which may arise from large blasts.)

This section also considers more common events that have fairly limited effects and damages, but may be associated with a significant degree of uncertainty about the area and population that could be struck by such impacts. Even though the number of celestial impact events has probably not increased in recent times, certain types of vulnerability have increased (see for example the description of the 1859 Carrington Solar Flare event, in the section describing Significant Events). Our public awareness of these possibilities has also increased, resulting in a need for additional information to inform citizens about the actual risks, effects that different types of celestial impact may have, and present-day means to prevent or mitigate some of the worst possible impact scenarios. Most significantly, the size of the human population, and the amount of land area it occupies, has changed greatly during the past century. The global population is nearly four times what it was a century ago, and (especially in the richer nations) this population growth has been accompanied by a much larger portion of the land area that has been built-up for urban uses. Just since World War II, the population of the United States has more than doubled, and even in areas with a relatively stable population, residential neighborhoods take up a lot more space today than they previously had in the period of time before the suburban "explosion." A random impact point today is more likely to affect lands that are developed to at least a moderate residential capacity, which could result in thousands of casualties.

Although most comets and asteroids have very consistent trajectories that change only very slowly, in terms of human history, Earth-threatening space bodies may still remain undiscovered by humans. There is also the possibility that their traditional orbits may be unexpectedly disrupted by collisions with other bodies, or by gravitational effects such as that exerted by Jupiter on Comet Shoemaker-Levy 9, which caused that comet's eventual impact into the planet. "Jupiter-family comets" are those in which a normal (safe) orbit of a comet or asteroid may be "suddenly" altered in a manner that causes it to become a threat to Earth. In either case (a newly discovered object or one whose course is changed), the possibility exists that a serious impact threat may suddenly be discovered. However, extensive observations and calculations have been taking place to identify and track all potential threats of this kind.

It is likely that the next major celestial impact will occur somewhere in the world other than Michigan, and that Michigan's role as part of the United States would at most involve the provision of support to the impacted area and its surroundings. If a major impact happens to occur in North America, then state-level mutual aid may result, and possibly even the intake of evacuees, as had taken place during the Katrina and Rita hurricane disasters of 2005. Several recent bolide events have been documented in the Great Lakes area, but have caused no known damage to the state's area during its European historical era over the past four centuries. It is possible that certain unexplained seismic events reported in the Upper Peninsula more than two centuries ago may have been caused by celestial impacts. For the most part, however, the meteorite hazard is important to know about mainly for preparedness and informational usefulness, rather than due to an actual pattern of damaging effects upon Michigan.

The space weather hazard, by contrast, is likely to cause one or more serious infrastructure failures in the near future, due to the extent of our reliance on complicated electronic and satellite systems that are vulnerable to disruption. In addition to power failures and phone communication breakdowns, it is also quite possible for the disruption of radio and navigational systems to cause risks for air and marine traffic. Even if cautious transportation providers are diligent about maintaining safety during such events, considerable economic impacts and delays can result from the electronic breakdowns caused by solar geomagnetic storm events.

Impact on the Public

A celestial impact from an object that is either sufficiently massive or fast-moving can have an effect that is comparable to nuclear blasts, in terms of the amount of energy released in the form of pressure (shock) waves and thermal effects (heat/fire). Additionally, major earthquake activity would be felt in areas that normally wouldn't have had to worry about such effects. An impact into major water bodies can cause intense tsunamis to occur, and severe winds could also result in extensive physical damages many miles (or hundreds of miles) away from the main impact site. Depending upon the mass and velocity of the meteorite, the impact on the public may range from the barely noticeable to the complete destruction of the entire area, with the most powerful impacts having effects similar to those described for nuclear attack (minus the radioactive fallout and electromagnetic pulse), earthquake, severe winds, wildfires, and storm seiches (shoreline flooding), all described in their own sections in this document. Space weather impacts will result in transportation delays and communication interference, and some cases may result in fatal transportation accidents, large economic losses, and widespread power supply interruptions.

Impact on Public Confidence in State Governance

If a major impact occurs in Michigan or the Great Lakes, many persons may feel disgruntled if no advance warning was able to be provided. There is probably not a widespread familiarity with this type of hazard, and popular conceptions may be rooted in televised or cinematic portrayals in which it was considered that part of the government perhaps "should have known" about a potential impact and been able to prevent it. One of the reasons that this hazard is now being included in state plans is to help provide information that will improve people's understanding of it. Moreover, since a significant celestial impact event could easily be mistaken for a nuclear blast by many persons, an educational process could be useful in overcoming the possible harm caused by such assumptions. For example, if a large bolide is seen, or actually damages an area, it will be helpful for people to have been familiar with what the event actually might be, rather than assuming that it was a deliberate hostile action that may involve secondary radiation and security impacts, or assuming that a mass evacuation or escalated level of security alert may be needed. Rather, if it is understood that there is a natural phenomenon that in some cases may resemble that of an atomic blast or explosive attack, then people's behavior and attention can be more properly guided toward activities and attitudes that are appropriate for a natural disaster rather than those for a homeland security alert. The potential impacts of space weather will require greater public awareness in order to build an understanding about existing weaknesses and the expense involved in correcting those weaknesses, where possible.

Impact on Responders

A small impact incident would not be likely to cause much risk for responders, unless the impact was upon a structure that became weakened to the point of potential further collapse. Larger impact incidents would be extremely unusual, but may be expected to require extensive search and rescue operations, as well as various firefighting operations and probable infrastructure failure impacts to be dealt with simultaneously. The presence of hazardous materials could also be expected at an impact site that had been urban in nature, or had involved key agricultural or infrastructure facilities. A catastrophic impact event could require extensive use of mutual aid and state/federal disaster and emergency assistance, with the possibility that all normal response resources would be disabled within the area of impact, and would need to be replaced by resources from adjacent local areas, or even from beyond the state. Underground sheltering would be a useful way to increase the odds of survival from the wind/shock/frame effects of a huge bolide event, which would likely pass quickly and then enable responders to deal with rescue operations, fires, infrastructure failures, and the organization of mutual aid. The impacts of space weather include interruptions in the function of radios, satellites, electronics, and even power supply systems that may be needed for emergency response. Response activities that involve electronic navigation technologies and Global Positioning Systems may need to fall back upon the use of less technologically advanced means to accomplish their mission.

Impact on the Environment

An extremely large impact, even if not in Michigan, could cause a National Emergency situation to arise, which Michigan may have to help to respond to and recover from (please refer to the chapter on catastrophic incidents). A direct meteorite impact on land could destroy an entire area, and cause fires, earthquakes, and other hazards for a large area around the impact. The same types of effects can also result from the atmospheric blast and heat impacts of a large bolide event, even if the celestial body itself does not strike the ground. A large impact in one of the Great Lakes could cause substantial flooding, seiche, and erosion impacts along areas at or near the lake's coasts. It has been speculated that space weather may be connected with global climate, but this is primarily due to the possibly coincidental occurrence of a "Little Ice Age" (lower average temperatures in America and Europe) during the same time that the Maunder minimum in solar activity was observed. The specific mechanisms that would underlie such a connection have not yet been figured out and therefore such a link should probably still be considered to be purely speculative. On the favorable side, solar activity helps to shield us from some of the cosmic rays that come from throughout the universe.

Significant Events

NOTE: Although many of the events listed here occurred out of state, some of them were nevertheless large enough to have direct impacts upon Michigan, due to the sheer magnitude of the impacts. Other events are included from a very long time ago, as well as smaller more recent events, to give an indication of the magnitude of what is possible. Some events describe "close calls" and events whose limited impact at the time could have been much greater had they affected a more densely developed location (for our current circumstances involve much greater population density and physical/infrastructure developments than had been present in the past). Some events are included because they help to indicate the range of threat posed by the hazard—events outside of Michigan usually represent the largest known events or threats, while events involving Michigan tend to represent the typical level of recorded impacts in the state.

Ancient-Archaic Events

Approximately 1.8 billion years ago – Sudbury, Ontario

One of the largest known impacts took place around Sudbury, Ontario, leaving impact effects that measure 155 miles in diameter. The impact site's geological structure had been discovered in 1883 but not fully explained until 1964. Debris ejected from the impact site was thrown as far as the Midwestern U.S., including

Michigan. This was an impact of global significance. The heat directly generated by this cataclysmic impact would have killed any humans within at least 500 miles from the impact site (which includes all of Michigan), if humans had been living in the area at the time.

Approximately 450 million years ago – Cass County

An impact, now designated Calvin 28, struck what is now southeastern Cass County, Michigan, and left effects that are still geologically detectable today. The Calvin impact area is about 5 miles in diameter, and is located mid-way between the Village of Vandalia and the Michigan-Indiana State Line. About the same time (in geological terms), a much larger impact occurred on what is now the northern coast of Lake Superior (the Slate Islands in Ontario) and formed an impact structure about 19 miles in diameter. The following map shows the Cass County impact area (Source: University of New Brunswick's Earth Impact Database website).

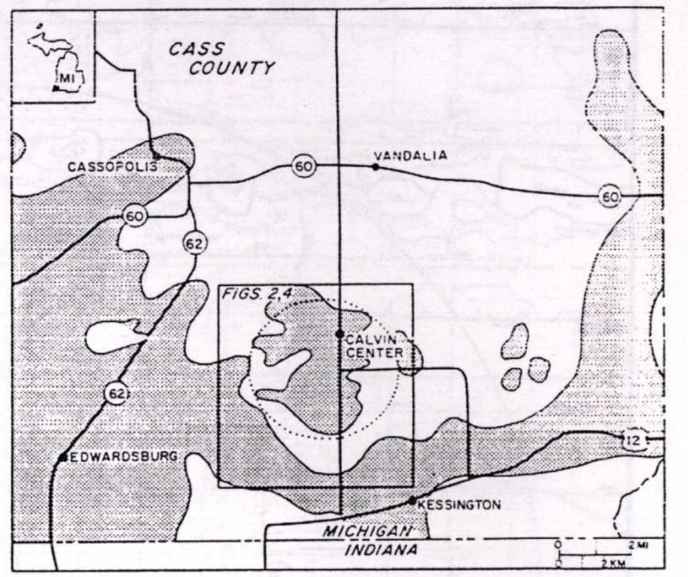


Figure 1. Map of the southeastern part of Cass County, Michigan, showing location of the Calvin 28 cryptoexplosive disturbance (dotted circle). Shaded area, Ellsworth Shale; unshaded area, Coldwater Shale.

Several hundred million years ago – Indiana and Ohio

A Kentland, Indiana impact leaves a crater estimated to have originally measured 8 miles in diameter. A smaller (5 mile diameter) Ohio impact later had Native American burial mounds built on its site, and is now known as the Serpent Mounds.

Approximately 65 million years ago – Global

A large impact on the Yucatan peninsula of Mexico (the impact area is now known as Chicxulub) took place at the end of the Cretaceous (geological) period, and thus has been considered to be a direct or contributing cause of the extinction of many prominent species of life on Earth at the time, including the large reptilian dinosaurs. There may be galactic cycles that make major, species-threatening impacts more likely during certain periods of time than others, with mass extinctions seeming to correlate with intervals of between 26 and 32 million years in length (over the past 250 million years), perhaps caused by some celestial event that sweeps Oort Cloud or Kuiper Belt objects from the outer parts of the Solar System toward Earth, or by the effects of a nearby star going supernova. Certain regions of the Milky Way Galaxy, which the Sun passes through on a grand cycle that repeats every 225 to 250 million years as it orbits the galaxy's center, may expose the Earth to more celestial bodies than are normally seen in the Solar System during the more stable, intervening time periods. Since the most recent mass extinction period was about 11 million years ago, there is no expected threat of this type during our lifetimes. The Chicxulub impact structure measures about 100 miles in diameter. Recently, evidence has been claimed for an even larger impact site, at around the same time, off the west coast of India. A surge in volcanic activity took place in the same geological time frame as the impact events and thus may have been a result of them.

About 37 million years ago – Ontario

Another impact occurred near the huge Sudbury, Ontario site (mentioned previously) and today is known as Lake Wanapitei, which is just under 5 miles in diameter.

About 50,000 years ago – Arizona

An impact forms the Barringer Meteor Crater in Arizona, which currently measures 570 feet deep and 1.2 miles in diameter. Evidence suggests that it was formed by an iron-nickel asteroid measuring about 100 feet in diameter, moving with an original velocity of 45,000 miles per hour. The impact probably caused hurricane-force winds more than a dozen miles from the impact site, the formation of a huge cloud of dust and debris, and the displacement of more than 300 million tons of rock.

Circa 900 C.E. or later – Alberta

An impact ("Whitecourt") at Alberta, Canada, leaves a crater that is more than 100 feet wide (now called the Brenham Crater).

Circa 1000 C.E. or later – Kansas

A Haviland, Kansas impact leaves a crater about 50 feet wide. (Also, during the same approximate time period, an impact occurred at Sobolev, Russia, leaving an impression about 3 times as wide.)

Modern Events

July 1, 1770 – International

Lexell's comet (D/1770 L1) was computed by astronomers as having passed only about 1.4 million miles from Earth (less than 6 times the average distance of the Moon, or about 1.5% of the distance to the Sun). This was the nearest such Earth encounter to be measured astronomically rather than in terms of its actual impact effects as a meteorite (until the very recent tracking of smaller and slower objects). Now considered to be a "lost comet," its orbital period had been calculated at the time (by Lexell) to be 5.6 years, eventually leading to the idea that space objects may be propelled toward Earth by a gravitational encounter with Jupiter—a circumstance that is one of the potential sources of comet/asteroid impact threats that would provide little or no advance warning. The comet was initially observed on June 15, 1770, and was last observed moving away from the Sun on October 3 of the same year.

September 1, 1859 – International

A large solar flare was briefly observed by astronomer Richard Carrington. Just before dawn of the next day, however, brilliant auroras were visible in skies around the world, telegraph systems severely malfunctioned, and various damages (and minor injuries) resulted from sparks and equipment failures. This was the first solar flare observation and it was also clearly seen that the phenomenon was connected with malfunctions in electronic communications systems on Earth. No solar flare of this magnitude has been seen in the 150 years since this occurred. Based upon evidence from arctic ice, it was estimated that the 1859 solar geomagnetic storm was the most intense in the past 500 years, nearly twice as much as the second-largest event. (Even though certain intensities have since been matched, no storm since has been able to simultaneously match this one, on all types of intensity measures.) Were such an event to happen again today, it has been estimated that tens of billions of dollars in damage would be done to the more than 900 satellites that orbit the Earth. These satellites are essential for the safe and smooth operation of airlines, spacecraft, and various communications systems.

1863 – Arabian Peninsula

An event more than 300 miles southeast of Riyadh, Saudi Arabian, left an impact site of probably at least five craters (Wabar Craters) in the desert, one of which was more than 100 meters in diameter. The impact compressed desert sand into rock. The date of the event is approximate, because the impact site itself was not reported until 1932, but was then considered in retrospect to match up with fireball reports that had come from the city of Riyadh in 1863. It has been calculated that the impact occurred with the force of a Hiroshima-sized atomic bomb, but fortunately in this case, it affected only an uninhabited desert area.

June 30, 1908 – Russia

A large impact event occurred in Tunguska, Russia (in Siberia), in which a large object blasted into the atmosphere in a manner that created a forceful, spectacular, and destructive impact. Although the object was evidently destroyed in the air (leaving no impact crater like so many rocky meteoroids have), the force of this destruction has been estimated as equivalent to between 5 and 30 megatons of TNT, flattening an estimated 80 million trees over an area of approximately 830 square miles (a surface area equivalent to that of a disc 32½ miles in diameter). Brilliant meteor impacts like this have been termed "**bolides**," since they can resemble fireballs and are observed as explosive, incendiary events. Unusual levels of acid rain followed the event. Recent research from Cornell University concluded that the event was "very likely" a comet impact (with most of its mass in the form of ice that would dissipate in the atmosphere), since high-altitude noctilucent clouds (which normally occur only with certain types of icy, high-altitude conditions) were sighted across Europe for several days (as much as 3,000 miles away), and caused the night skies to glow. Estimates about the frequency of this scale of impact vary from once every thousand years to once per century.

May 1921 – International

An extremely strong geomagnetic storm occurred—the strongest such storm since 1859. According to one study, if a storm of this magnitude were to occur today, it could result in large-scale electrical blackouts that would affect more than 130 million persons across the northwestern U.S. (including Michigan) and the Pacific Northwest. These estimates were based upon estimates of regions susceptible to power grid collapse, and the 1921 storm was considered to be about 10 times as strong as the one that did cause power failures in 1989. Extra-high-voltage transformers were considered to be a particular vulnerability in these projected blackout areas, with places like New Hampshire, New Jersey, and Pennsylvania at particularly high risk in the interconnected grid.

February 12, 1947 – Russia

A bolide event that included many meteorites took place in far-eastern Russian Siberia (Sikhote-Alin), fortunately occurring in a relatively isolated and undeveloped area, between China and Japan. The event was reported as a fireball, brighter than the Sun, at 10:38 am (local time). As the bolide descended at an angle of 41 degrees, it left a trail of smoke and dust 20 miles long that remained visible for several hours. The meteorite was broken into fragments as it fell at roughly 31,000 miles per hour. Upon reaching an altitude of about 3.5 miles, the bolide culminated in a giant explosion, scattering its remaining debris over an impact area of about one-half square mile. The largest impact crater in this area measured 85 feet wide and 20 feet deep. The total mass of all the meteorites from this event has been estimated as just under 1,000 tons, with the largest fragment later weighed at 1,745 kilograms and displayed in Moscow.

September 17, 1966 – Lake Huron

A bolide event occurred over Lake Huron, Michigan, involving an air blast estimated as the equivalent of 1/3 ton of TNT, approximately 8 miles above the surface of the water. Although no material from a meteorite was found to help determine more information about the size and characteristics of this meteor, this is not surprising since the location of the event probably placed any meteorite remnants at the bottom of Lake Huron. The bolide illuminated the whole of south-western Ontario and adjacent regions at about 8:48 pm, as it was seen traveling northwest across Lake Erie and the tip of Ontario, toward Lake Huron. At least a dozen loud "detonations" were reported from the Ontario area near the lake a few minutes after the fireball's passage. Astronomers later calculated that the meteor was about 8 miles up as it crossed over Lake Huron, and probably reached the lake's surface fewer than 18 miles west of the city of Kincardine, Ontario. The meteor was traveling about 10.6 miles per second (38,000 miles per hour) and was brightly luminous for at least 10 seconds.

February 8, 1969 – Pueblito de Allende, Mexico

A large shower of stony meteorites fell near a village in the Mexican border state of Chihuahua. More than two tons of meteorites fell in that incident.

August 4, 1972 – Illinois

A huge solar flare ended up causing the failure of long-distance telephone communications across Illinois. AT&T redesigned its power system for transatlantic cables as a result of this event.

August 10, 1972 – Western U.S. and Canada

Since the angle of approach varies widely, some meteors simply graze or bounce off of the atmosphere. In 1972, such a fireball was seen from Utah to Alberta.

January 1978 – International

A Soviet satellite, Cosmos 954, which had been launched in September of 1977, was being monitored by U.S. agencies and by November was found to have a decaying orbit. By January, it had become apparent that the satellite had lost its attitude stabilization system. Such satellites were known to be powered by small nuclear reactors, using fuel that was 90 percent enriched Uranium-235. Thus, whenever and wherever this satellite fell to Earth, it had the potential to contaminate things and persons who came into contact with it. The U.S. National Security Council arrived at an estimate that there was only about a 1 in 10,000 chance that a human would be injured in the crash, but because of the political aspects of an enemy nation's nuclear satellite crashing onto friendly territory, it became important to treat the incident with more weight than what that small risk might normally be credited with. Operation Morning Light was thus created, in December of 1977, with the Department of Energy given lead responsibility for the possibility of a domestic crash site. Even though a crash site for the projected landing orbit was only supposed to have an 8% chance of being on land, plans were made for such a contingency, which would involve the finding of radioactive debris, decontamination of affected land areas, and the treatment of any persons within an unsafe distance of such debris. After about 10 days of careful inquiries with the Soviet government, various types of confirmation were received about the satellite's nature and condition. On January 24, the satellite entered the atmosphere over Queen Charlotte Island, British Columbia, and at 6:53 am, finally crashed near the Great Slave Lake, just north of the Province of Alberta, in Canada. Aircraft and Nuclear Energy Search Teams were then dispatched to Canada, to assist with clean-up operations.

July 11, 1979 – International

The Skylab Space Station, which had been put into orbit in 1973 but abandoned in 1974, had its orbit finally deteriorate to the point where it plunged to Earth. Delays in the launch of the Space Shuttle program prevented the station from being salvaged by restoring it to a sustainable orbit. Instead, considerable uncertainty was expressed in the media about where the station might return to Earth, and with what potential for destructive impacts. Skylab re-entered the atmosphere on July 11 and the calculated area at-risk turned out to be in the Southern Hemisphere around the Indian Ocean. Debris impact areas on land were identified in Western Australia, the largest being a heavy metallic fragment (perhaps 5 feet in length).

March 13, 1989 – Canada and Eastern United States

Geomagnetic storms caused by a huge solar flare caused widespread disruptions in the transmission of electrical power, causing a widespread blackout across most of Quebec and affecting 6 million persons for a period of up to 9 hours. Specifically, when five transmission lines went down, the system was unable to withstand the loss of their 21,350 megawatt load, and collapsed within the subsequent 90 seconds. The blackout closed schools and businesses, shut down the Montreal Metro Airport, and delayed flights from other airports. Street traffic backups took place, since traffic signals and traffic control systems no longer functioned smoothly. Workers in downtown Montreal were stranded in dark offices, stairwells, and elevators. Elsewhere, power surges caused by the geomagnetic storm (geomagnetically induced currents, or GICs) caused power transformers in New Jersey to be overloaded and damaged. The functioning of long-distance telephone cables were also affected by auroral currents, major power substations experienced voltage swings, generators went offline, and the U.S. Air Force temporarily lost its ability to track satellites. Costs from the loss of power exceeded $100 million, including stalled production processes, idled workers, and spoiled products. This was considered to be the strongest geomagnetic storm of the space age.

October 9, 1992 – New York

The "Peekskill Meteorite" damaged a parked car in Peekskill, New York, after creating a bright fireball in the sky that was seen across several states. The original meteor (estimated to be 1 to 2 meters wide) had fragmented at a height of about 41.5 km, then again about 20 seconds later, until it was under a foot in diameter.

January 1994 – Canada

Inclement space weather caused electric charges to build up and then discharge within the electronic components of two expensive communications satellites. One satellite was disabled for about 7 hours, due to damage to its control electronics. A second satellite went out of service entirely, when its backup systems also became damaged, requiring 6 months of service before its functions were restored. The satellite disruptions prevented news information from being electronically delivered to 100 newspapers and 450 radio stations. Television and data services to more than 1,600 remote communities broke down with the second satellite failure. Telephone service in 40 communities was also interrupted. Total costs of the event were estimated at between 50 and 70 million U.S. dollars.

July 15 to 24, 1994 – International

Comet Shoemaker-Levy 9 crashed into the planet Jupiter, after being broken into 21 fragments by gravitational forces, and caused enormous impacts, which quickly became visible to telescopes on Earth. (The impact took place on the far side of Jupiter, but the planet quickly rotated and allowed the impact points to be visible). The energy released by this impact was estimated as greater than many thousands of 50-megaton nuclear bombs, as the comet's debris was vaporized and released enormous amounts of heat, temporarily exceeding the amount given off by the entire (exothermic) planet as a whole and also exceeding the temperature of the surface of the Sun. The impacts caused atmospheric spots to appear that were comparable in size to the diameter of the Earth. The comet had first been detected by astronomers only 17 months prior to its impact. It was calculated that on the comet's previous approach toward Jupiter on July 7, 1992 (which tore it into fragments), its distance from the planet was only 16,000 miles (less than the circumference of the Earth). It was estimated that the largest fragment of the comet may have exceeded 2 miles in diameter. As a result of this impact, the U.S. Congress asked NASA to propose how to identify and track all large space objects with the potential to impact the Earth.

March 19, 1996 – International

A celestial "close call" involved asteroid 1996 JA1 (large enough to cause catastrophic damage), which came within 280,000 miles—nearly as close as the Moon.

January 11, 1997 – International

A satellite that had cost $200 million was incapacitated by the impact of a Coronal Mass Ejection. After efforts to restore the satellite's function failed, it was officially decommissioned.

September 1, 1997 – Salem Township (Washtenaw County)

After numerous persons reported a bright daylight meteor and sonic booms, the object broke up into at least three parts. One meteorite (called the "Worden Meteorite") then struck a residential garage roof (in Salem Township, midway between the villages of Salem and Brookville), as the family was nearby working in their back yard. They had heard a whistling sound passing overhead, and then investigated a boom and crash, finding the garage full of plaster dust, pieces of drywall, and insulation. There was a dent in the roof of a car that was parked in the garage, and the meteorite itself was found on the floor nearby, along with a couple of associated fragments. The large meteorite weighed about 1.5kg, and its dimensions were about 6 inches long, 4 inches wide, and an inch thick.

April-May, 1998 – International

The failure of the attitude control system of an expensive Galaxy IV satellite (the cost of such satellites is usually on the order of $200 to $250 million) disrupted the function of about 45 million pagers. Various other satellite problems were noted, and researchers eventually concluded that these problems were "caused, or at least exacerbated by" the impacts of geomagnetic conditions originating from "highly disturbed" solar conditions. Although the satellite problems occurred in May, weeks of problematic space weather that had started back in April was considered to have eventually led up to May's events.

June 14, 2002 – International

Another "near miss," in celestial terms, as asteroid 2002 MN passed within 75,000 miles of the Earth, but wasn't spotted until three days after it had already passed. An impact from the asteroid would have been of Tunguska-like force.

Feb 1, 2003 – National

The Space Shuttle Columbia broke apart violently when returning from a mission, causing a widespread alert about the potential for falling debris across the southwestern United States. More than 2,000 debris impact sites were eventually reported, but fortunately these were predominantly in sparsely populated areas. NASA issued warnings that the shuttle debris could contain hazardous materials and that it should remain untouched (and instead be reported to authorities upon discovery).

March 26, 2003 – "Park Forest event" in Suburban Chicago, Illinois

Hundreds of meteorites fell across residential areas in the suburbs of Chicago. Although meteors were visible from Michigan and the meteorites landed fairly close to Michigan territory, it must be noted that this event is highly unusual, having been described as "the most densely populated region to be hit by a meteorite shower in modern times." Coincidentally, the area of impact was in the midst of numerous highly-trained experts associated with the University of Chicago and other scientific institutions. The original meteoroid was calculated to have been between 1 and 7 thousand kilograms (possibly more) before it broke apart in the atmosphere. About 30 kilograms of meteorite fragments were recovered, the largest of them weighing 5.26kg. Numerous holes were punched through windows, roofs, and ceilings in homes, and also a fire station. One roof hole was caused by a meteorite that weighed only 545 grams. There were about 18 documented fragments of about that size or larger across a couple of square miles of neighborhoods.

October and November, 2003 – International

Geomagnetic storms took place in late October and November, and although power grids had learned from the March 1989 event and were better able to withstand the storms' effects, there were some heavy impacts upon the aviation sector from this event. The FAA had implemented a WAAS (Wide Area Augmentation System) to better guide navigation and aviation system control, and a part of what WAAS supports is the ability of air traffic to maintain safe distances from each other. The vertical navigation component of WAAS was disabled for approximately 30 hours across most of the United States during the late October storms.

January 2005 – International

Space weather at this time included solar radiation storms. In addition to the loss of HF radio communications, such storms can cause elevated radiation exposure to persons in aircraft flying at high latitudes (e.g. across polar regions). The use of polar routes has increased dramatically since the 1990s, since such routes can reduce travel time and fuel costs (by avoiding strong wintertime headwinds). Aircraft must divert to lower-latitude routes during such storm events, resulting in delays, increased flight times, missed connections, higher costs, and greater fuel consumption.

December 2005 – International

A geomagnetic storm caused the disruption of satellite-to-ground communications and GPS (Global Positioning System) navigational signals. Although this disruption only lasted about 10 minutes, it threatened the safety of commercial air flights and marine traffic during that time.

December 6, 2006 – International

A burst of solar radio wave energy caused a disruption in the function of GPS units across the entire sunlit side of the Earth (the Western hemisphere in this case). Some users of navigation systems found their capacities disrupted for many minutes, which was of particular significance for military aircraft.

September 20, 2007 – Southern Peru

After a loud explosion was heard, residents of an isolated village found a large crater measuring 41 feet in diameter near Lake Titicaca and filled with water. A 1.5 magnitude earthquake was detected in the area. The unusual aspect of this incident is that many villagers subsequently reported symptoms such as headaches and nausea. It has been proposed that the impact of a meteorite, along with the heat that was generated, caused the release of toxic fumes from the ground.

February 4, 2011 - International

An asteroid designated as 2011 CQ1 was the closest “near miss” on record so far, as this object came only about 3,400 miles away from Earth. Earth's gravitational pull at that distance was strong enough to change the asteroid's trajectory by 60 degrees, indicating just how close the object was, in astronomical terms.

June 27, 2011 - International

An asteroid designated as 2011 MD passed only 7,600 miles above the Earth’s surface. It was discovered by LINEAR and its size was less than 20 meters in diameter. The object was close enough to markedly change its trajectory as it passed.

February 15, 2013 – Chelyabinsk, Russia

A meteor became visible in the sky, and was soon followed by a shock wave that shattered windows throughout a wide portion of the major Russian city of Chelyabinsk. About 1,600 persons were reported as injured by shattering glass throughout the city. Damage to a couple of industrial facilities also resulted, as the blast wave caused large doors to buckle and weakened structural components to collapse. The meteorite’s impact location was later located in a rural area, much reduced in size from the body that had originally blazed through the atmosphere. This was the first incident in which many injuries occurred as a result of this type of hazard. The physical size of this meteorite was much smaller than the Sikhote-Alin event of 1947 or the Tunguska event of 1908. It is fortunate that only the meteoritic blast wave was felt by the city, but this event is strongly indicative of the extent of damage that this hazard can cause. The destruction could have been far worse if the trajectory of the meteorite had been different. Meteorite fragments weighing about ¾ ton were later retrieved from the impact site at Chebarkul Lake, about 40 miles away. The meteorite was determined to have originally been one of the Apollo Near-Earth Asteroids, approximately 60 feet in its original size and with a mass of about 11,000 tons before it started to burn up in the atmosphere. The total impact energy was calculated by NASA to be the equivalent of about 440 kilotons of TNT. Purely by coincidence, many persons were already thinking about asteroids, because they were anticipating the near-Earth approach of an already-known body, asteroid 2012 DA14, which passed harmlessly by the Earth about 16 hours later, with a completely different (and thus unrelated) approach directory than the meteorite had shown. The Chelyabinsk meteorite had been traveling west-northwest above the earth’s northern hemisphere, approaching from the general direction of the Sun, but the path of asteroid 2012 DA14 was going in a nearly perpendicular direction, and at its nearest it was about 17,000 miles away from the Earth’s surface. The temporal proximity of the two bodies was mere coincidence, although 17,000 miles is quite close, in celestial terms, for a 150-foot diameter asteroid to pass by, allowing it to be clearly photographed from the Earth during its passage.

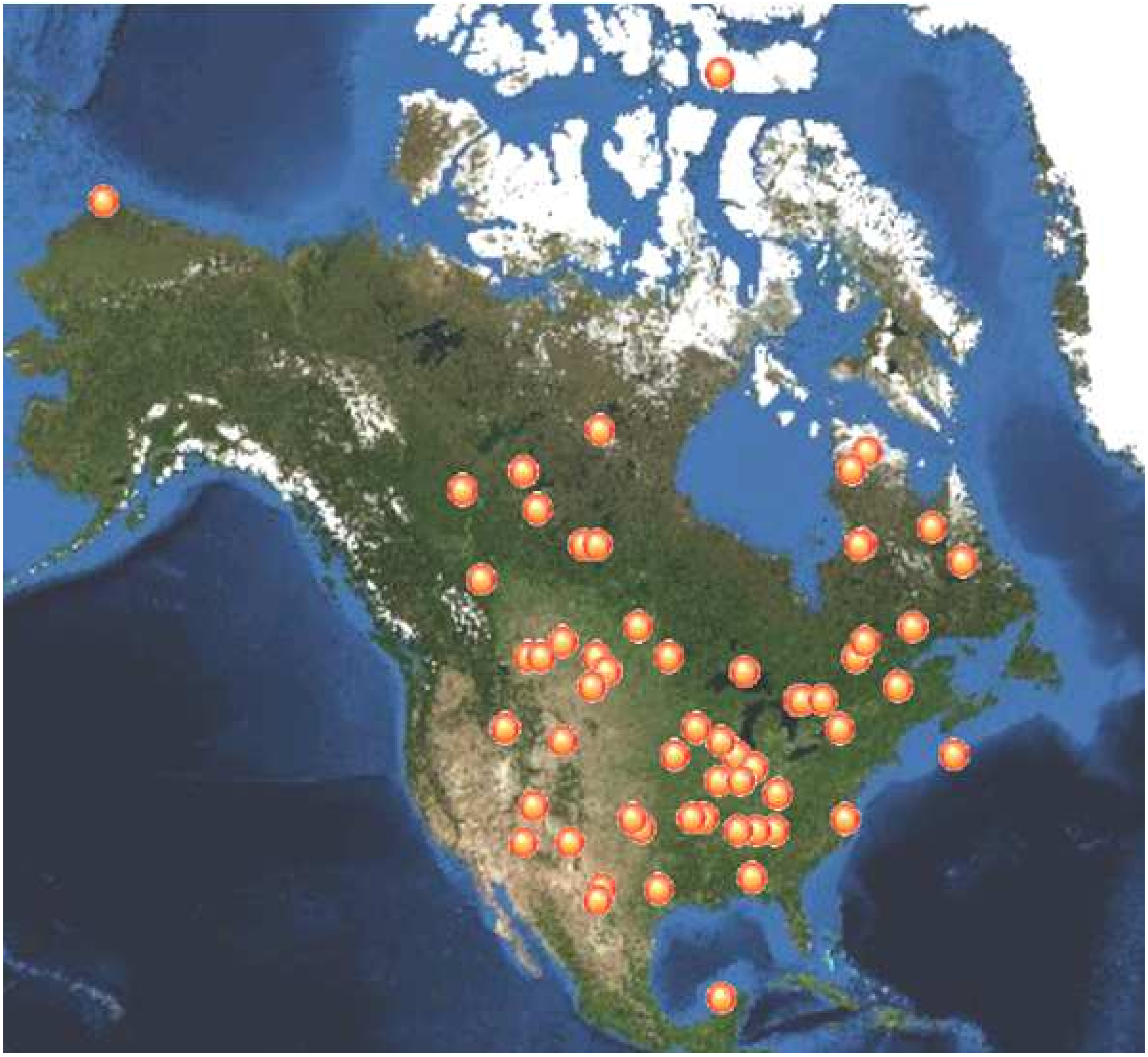


Image showing identified impact crater sites across the United States and Canada
(Map based on information from the Impact Database website – http://www.unb.ca/passc/ImpactDatabase/NorthAmerica.html)

Programs and Initiatives

In recent decades, a number of programs and research projects have examined this hazard, sought additional information about near-Earth objects (NEOs), and developed models of the potential risks and effects of an impact. Although most historic meteors went unnoticed (or unrecorded as such) in earlier times, today's satellite systems allow practically every meteor to be detected as it ignites in the atmosphere.

Near-Earth Object Detection Programs

Various agencies and universities have set up or coordinated in the creation of detection programs designed to locate and measure the characteristics of Near-Earth Objects such as "Apollo asteroids" that cross the orbit of the Earth. (It has been estimated that there are about 200 such asteroids with diameters of at least 1km, which would thus be capable of catastrophic damage if an impact were to occur. It has also been estimated, by NASA, that fewer than 10% of the estimated NEOs larger than a half-mile in diameter have yet been detected.) Most of these detection programs involve systematic telescope surveillance, measurements, complex modeling and orbital projection. Programs include the following:

- Lincoln Near-Earth Asteroid Research (LINEAR) project – at MIT, funded by NASA and the USAF.
- Lowell Observatory NEO Survey (LONEOS) program – in Flagstaff, Arizona.
- Near-Earth Asteroid Tracking (NEAT) system – operated by NASA's Jet Propulsion Laboratory in conjunction with the U.S. Air Force on Mt. Haleakala, Hawaii. The goal of NASA's 1998 Near-Earth Object Program was to locate at least 90 percent of all NEOs that are at least 1km in diameter.
- Palomar Planet-Crossing Asteroid Survey
- Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) – Hawaii program supported by the U.S. Air Force.
- Raptor – a stereoscopic observation system operated by Los Alamos National Laboratory.
- The Sentry System – of the NASA Jet Propulsion Laboratory
- Spaceguard – started by NASA in 1998, a global survey devoted to asteroid analysis.
- The Spacewatch program – run by the University of Arizona in Tucson at Kitt Peak, Arizona.
- Various space missions have occurred to gather more information about asteroids and comets, and more are planned for the future. Some past missions have included Vega 1, Vega 2, Giotto, Suisei, and Sakigake (1986 flybys of Halley's Comet); Galileo (1995 observations of the Shoemaker-Levy comet impact); Near-Earth Asteroid Rendezvous (NEAR—asteroid investigations from 1997 to 2001); Deep Space 1 (comet rendezvous in 2001), Stardust (comet material collected and returned for analysis in 2006); Hayabusa (aka MUSES-C – asteroid landing and probing form 2005 to 2010); Rosetta (asteroid flybys from 2008 to 2010, and comet interception mission scheduled for 2014-2015); and Deep Impact/EPOXI (comet rendezvous in 2005 and flyby in 2010). Additional missions can be expected to provide even more information.

More information about these programs can be found at their associated web sites on the internet.

Solar Monitoring and Measurement Programs

Various spacecraft are gathering data on solar flares, coronal mass ejections (CMEs), and charged-particle emissions (solar storms and space weather). These include:

- The Solar and Heliospheric Observatory (SOHO) (http://sohowww.nascom.nasa.gov/) is a collaborative international project between the U.S. National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA). It was launched in 1995. Among its solar studies, it tracks the intensity of solar winds and flares, and has also been responsible for the discovery of 2000 comets.
- Hinode – A Japanese satellite that engages in solar missions coordinated with other space agencies around the world, Hinode employs optical, ultraviolet, and X-ray equipment that measures the Sun's magnetic field, the Sun's corona (turbulent outer atmosphere), and the solar particles that are radiated.
- Solar Terrestrial Probes (STP) – Currently, the Solar Terrestrial Relations Observatory (STEREO) is the third of NASA's Solar Terrestrial Probes program and has been engaging in 3-D observations, imaging, and measurements of solar activity since 2006. Using a pair of spacecraft, the combined views cover most of the solar surface at all times, including the far side of the Sun, and make use of extreme ultraviolet waves to better detect and analyze coronal activity. A phone application is available from NASA that allows solar monitoring and the receipt of alerts to be transmitted to users' phones. The STEREO web site is located at

http://www.nasa.gov/mission_pages/stereo/main/index.html. On February 3, 2011, the two STEREO craft reached positions directly opposite each other, 180 degrees apart on each side of the Sun, allowing the entire surface to be monitored simultaneously. A Magnetosphere Multiscale (MMS) mission is planned for 2014, and will study three important plasma processes in the Earth's magnetosphere, to better understand space weather processes.

- Advanced Composition Explorer (ACE) – Launched in 1997, NASA's ACE provides solar wind monitoring and measurement in nearly real-time. From its space location at a point of gravitational equilibrium between the Earth and the Sun, ACE provides one hour of advance notice about impending geomagnetic activity that can disrupt communications and/or overload power grids. ACE instruments provide information about energetic ions and electrons, magnetic field vectors, high energy particle flux, and solar wind ions. The ACE web site is found at http://www.swpc.noaa.gov/ace/.
- Solar Dynamics Observatory – This program was designed by NASA to help understand the causes of solar variability, and its impacts on Earth. Launched in 2010, the mission focuses on the Sun's magnetic field, solar coronal activity and plasma, space weather, and the irradiance underlying planetary ionospheres. The SDO web site is at http://sdo.gsfc.nasa.gov/mission/about.php.

NOAA/NWS Space Weather Prediction Center
A web site at http://www.swpc.noaa.gov/ allows continuous access to information about space weather, including the convenient classification of space weather into NOAA's convenient 5-category schemas (e.g. from G1 to G5). Alerts and warnings are also accessible through this web site, along with a number of Space Weather User Groups, covering topics such as navigation, radio, electric power, and satellite operators.

NASA Asteroid Redirect Mission
This newly developing mission has the goal of detected, capturing, and redirecting an asteroid into a safe orbit. For more details, refer to the NASA overview presentation at http://www.nasa.gov/pdf/740684main_LightfootBudgetPresent0410.pdf.

Grid Reliability and Infrastructure Defense Act (GRID)
In 2010, the U.S. House of Representatives passed an act that included the following language specifically directed toward mitigating some of the impacts of geomagnetic storms:
"Geomagnetic storms.--Not later than 1 year after the date of enactment of this section, the Commission shall, after notice and an opportunity for comment and after consultation with the Secretary and other appropriate Federal agencies, issue an order directing the Electric Reliability Organization to submit to the Commission for approval under section 215, not later than 1 year after the issuance of such order, reliability standards adequate to protect the bulk-power system from any reasonably foreseeable geomagnetic storm event. The Commission's order shall specify the nature and magnitude of the reasonably foreseeable events against which such standards must protect. Such standards shall appropriately balance the risks to the bulk-power system associated with such events, including any regional variation in such risks, and the costs of mitigating such risks."
The full text of the act can be found at http://www.fas.org/irp/congress/2010_cr/grid.html.

The celestial impact hazard has not yet been identified as one of the most significant hazards in any of Michigan's local hazard mitigation plans.

Mitigation Alternatives for Celestial Impacts

- Advance planning for catastrophic scenarios. For example, the U.S. Air Force used an asteroid strike for its December 2008 Interagency Deliberate Planning Exercise. The after-action report for that exercise was posted online at http://neo.jpl.nasa.gov/neo/Natural_Impact_After_Action_Report.pdf. An asteroid detected at a distance equivalent to that of the Earth's Moon could still give 8 hours of advance warning for the evacuation of coastal areas (to mitigate loss of life from a projected sea impact).
- Continued surveillance and analysis of Near-Earth Objects, and support for agencies that are engaged in such work. For example, since 1975, the Department of Defense has amassed extensive data about meteors entering the atmosphere, finding that hundreds per year explode in the atmosphere with explosive energy of at least 1 kiloton.
- Existing technologies would allow the diversion of a large asteroid or comet, if a sufficient lead time is available. Objects on a collision course 10 to 100 years in the future can be diverted or reduced by the use of conventional rockets and explosives. (Such action would be coordinated in the United States by the Departments of Defense

and Energy, and would likely include international partners.) Explosives would require knowledge of an object's composition to be effective. Laser targeting could be used to change an object's velocity, although weeks or months may be required to obtain a large enough effect. With a sufficient amount of warning time (on the order of years), other mitigation techniques could include attaching a solar sail to the object, an interception/landing mission, and/or use of the "Yarkovsky effect" in which asteroid temperatures could be changed to affect its orbit.

- Various space missions have occurred to gather more information about asteroids and comets, and more are planned for the future. Some past missions have included Vega 1, Vega 2, Giotto, Suisei, and Sakigake (1986 flybys of Halley's Comet); Galileo (1995 observations of the Shoemaker-Levy comet impact); Near-Earth Asteroid Rendezvous (NEAR—asteroid investigations from 1997 to 2001); Deep Space 1 (comet rendezvous in 2001), Stardust (comet material collected and returned for analysis in 2006); Hayabusa (aka MUSES-C – asteroid landing and probing from 2005 to 2010); Rosetta (asteroid flybys from 2008 to 2010, and comet intercept mission scheduled for 2014-2015); and Deep Impact/EPOXI (comet rendezvous in 2005 and flyby in 2010). Additional missions can be expected to provide even more information.
- Awareness campaigns for industries and systems involving satellite communications, GPS, or radio communications that could be disrupted by solar flare (space weather) activity. In addition to the use of GPS for navigation, aviation, and military applications, it is also important for offshore drilling operations, precision farming, transportation, and mapping and surveying.
- Operating procedures that include back-up systems allowing complex systems (e.g. air traffic control) to continue to function when key technological systems (e.g. GPS, radio communications, satellites) malfunction. For example: the maintenance of "legacy" non-GPS navigational systems as a back-up, and the use of new GPS signals and codes to remove ranging errors.
- The use of special procedures, equipment, and redundancies by utility systems (e.g. electrical power and pipeline systems) to minimize the potential for geomagnetic effects to cause inappropriate shutdowns and system damage. For example: the provision of reserve capacity may offset the effects of geomagnetic storms, and the temporary disconnection of components for their own protection.
- Additional back-up satellites, for communications and navigation, will be needed to limit the damaging effects of a major solar storm, which may put current satellite equipment out of action and require their rapid replacements. The importance and cost of satellite systems may not be well-known to the general public. As of 2009, the existing fleet of 250 commercial satellites constituted a total investment of about $75 billion, and involved an annual revenue stream estimated at over $250 billion.